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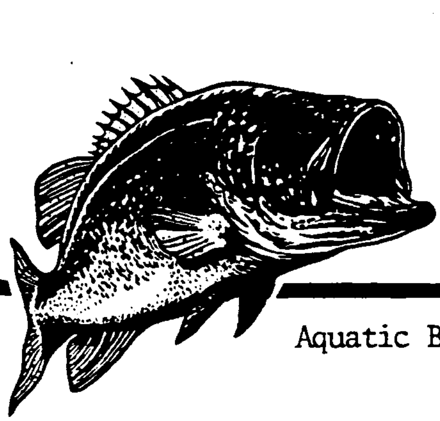
BIOLOGICAL CONTROL OF AQUATIC MACROPHYTES BY HERBIVOROUS CARP
Part III. Stocking Recommendations for Herbivorous Carp and Description of the Illinois Herbivorous Fish Simulation System

Aquatic Biology Section Technical Report

M. J. Wiley, P. P. Tazik, S. T. Sobaski, and R. W. Gorden



Final Report
Federal Aid Project F-37-R

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BIOLOGICAL CONTROL OF AQUATIC MACROPHYTES BY HERBIVOROUS CARP

Part III. Stocking Recommendations for Herbivorous Carp and Description of the Illinois Herbivorous Fish Stocking Simulation System

Final Report, Federal Aid Project F-37-R

by

M. J. Wiley, P. P. Tazik, S. T. Sobaski, and R. W. Gorden

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March 1985

Project F-37-R, Effects of Using Hybrid Carp to Control Aquatic Vegetation, was conducted under a memorandum of understanding between the Illinois Department of Conservation and the Board of Trustees of the University of Illinois. The actual research was performed by the Illinois Natural History Survey, a division of the Department of Energy and Natural Resources. The project was supported by funds from the U.S. Fish and Wildlife Service (Dingell-Johnson) and the Illinois Natural History Survey. The form, content, and data interpretations made in this report are the responsibility of the University of Illinois and the Natural History Survey, and not that of the Illinois Department of Conservation.

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FOREWARD

This report consists of three separate parts to facilitate distribution and aid in comprehension. Part I contains the Executive Summary for this project; it gives a brief description of major results and a series of recommendations to the Illinois Department of Conservation regarding the status of the grass carp and its genetic derivatives in Illinois. Part II contains a series of chapters detailing our studies of the biology and ecology of these fish. Part III contains stocking recommendations for Illinois and a description of the computer simulation model upon which they are based.

ACKNOWLDGMENTS

Many people have contributed to this investigation over the four and a half years since it began in 1980. A complete list of research participants has been given and we are grateful for the cooperation and professional contributions of each and every person listed. Beyond those actually conducting the many research tasks involved in a study of this scale, there are a number of people who deserve special thanks: J. M. Malone of J. M. Malone and Sons Enterprises, who provided us with fish and technical assistance throughout the study; Jana Waite and Sue Peratt, who provided secretarial, editorial and occasionally manual assistance for which we are most thankful; Jim Allen, Peter Paladino, and Steve Harrison of the Illinois Department of Conservation, with whom we have interacted throughout the study and for whose cooperation and patience we are grateful; Dr. A. R. Brigham and associates, who performed all of our laboratory water quality analyses; and Dr. Sue Wood and associates, who handled most of our tissue analyses and calorimetry. We also thank B. F. Goodrich and Environmental and Process Equipment, Unlimited for supplying the PVC biofiltration media.

GUIDE TO CHAPTERS BY D-J JOB DESIGNATION

In order to facilitate the identification of report contents with federal study and job classifications used in the AFA for F-37-R, the following guide is presented. In addition to listing chapters in this final report, references to appropriate publications supported by this contract are also given.

STUDY 101: A comparison of the effects of hybrid grass carp and selected aquatic herbicides on aquatic vegetation and the sport fishery.

Job 101.1. Determination of existing aquatic macrophytes--Part 2: Chapter 5.

Job 101.2. Control--Part 2: Chapters 2 and 3; Gorden et al. 1982

Job 101.3. Water quality--Part 2: Chapter 3

Job 101.4. Establish of fish populations--Part 2: Chapter 3

Job 101.5. To determine growth characteristics--Part 2: Chapters 1, 2, and 3.

Job 101.6. Reproduction--Part 2: Chapters 4 and 5

STUDY 102. The effects of the control of aquatic vegetation by hybrid grass carp and by herbicides on the rates of decomposition, nutrient cycling and flow and the subsequent effect on the bass, bluegill, and catfish populations.

Job 102.1. Measurement of invertebrate and microbial populations--Part 2: Chapter 3

Job 102.2. Rates of deocmposition of aquatic macrophytes--Part 2; Chapter 3; Gorden et al. 1982

Job 102.3. Nutrient cycling studies--Part 2: Chapter 3

Job 102.4. Energy flow--Part 2: Chapter 1

Job 102.5. Systems analysis--Part 3; Wiley et al. 1983

STUDY 103: Genetic composition and reproductive capability of F1 hybrid carp.

Job 103.1. Genetic composition and uniformity--Executive summary; Magee and Philipp 1982

Job 103.2. Gonadal development--Part 2: Chapter 5

Job 103.3. Reproductive capability--Part 2: Chapter 4

Chapter 1

STOCKING RECOMMENDATIONS

The stocking recommendations made in this report are based on a series of analyses using the Illinois Herbivorous Fish Stocking Simulation System (IHF3S), a computer model in which bioenergetics and feeding characteristics of herbivorous carp are coupled with seasonal aquatic plant dynamics to produce estimates of the level of plant control achieved with different stocking strategies. A complete description of IHF3S can be found in Chapter 3 of this report. In this chapter we present a systematic summary of our stocking recommendations for triploid grass carp in Illinois. Although IHF3S can be used to examine diploid (normal) grass carp stocking strategies, no stocking recommendations for diploids are made here, in keeping with our recommendations to prohibit diploids in Illinois (Wiley and Gorden 1984a).

APPROACH

Answering the question of "how many fish should be stocked?" for a particular plant control situation is, unfortunately, not as straight forward as it might first appear. The decision to use herbivorous carp to control macrophyte populations immediately demands a second decision about the degree of plant reduction desired. The grass carp is a potent bio-technology, fully capable of completely stripping most bodies of water in Illinois of all macroscopic plant growth. Total eradication of plants may be neither aesthetically nor ecologically desirable in most situations but may be entirely acceptable in others. Stocking rate is the primary mechanism available to achieve varied levels of control with these fish. Obviously then, the number of fish to be stocked depends upon the amount of plant control one wishes to achieve.

Even when the degree of control has been clearly specified, there are several key factors which affect the amount of growth and consumption (i.e., plant control potential) that can be expected from stocking a given number of grass carp. These factors include:

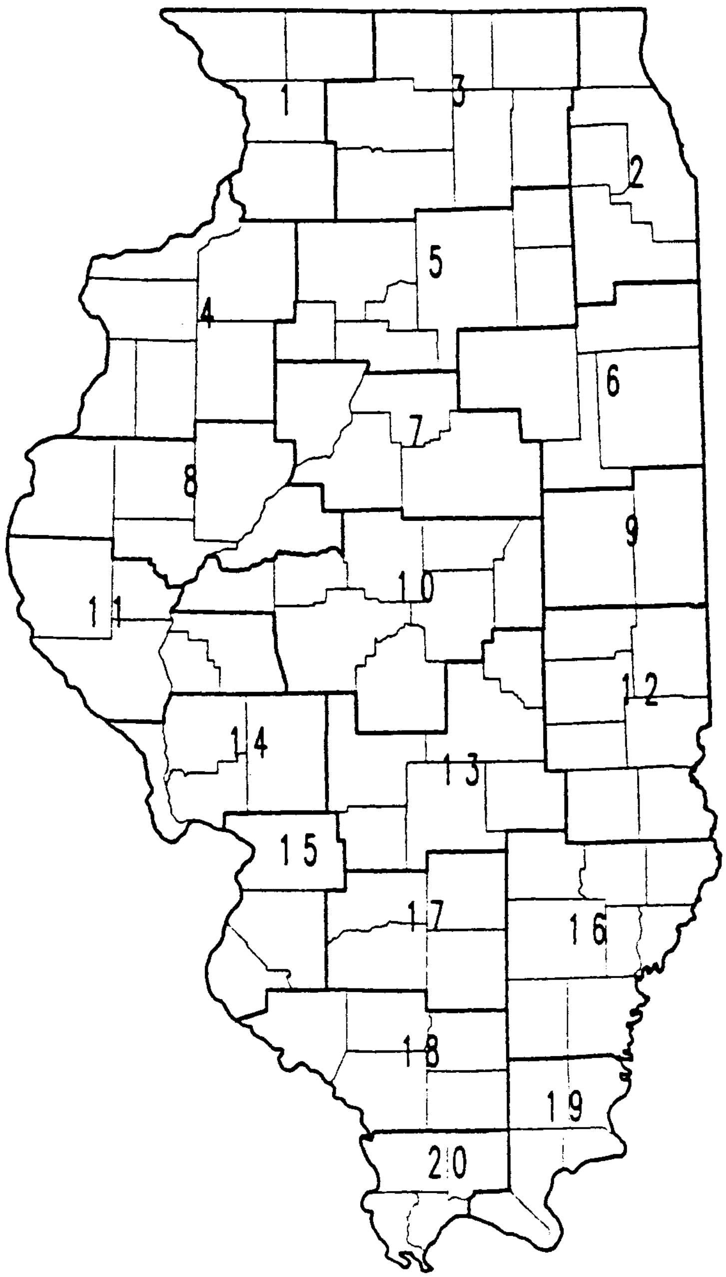


Fig. 1-1. Twenty climatic regions in Illinois as designated by the Illinois State Water Survey.

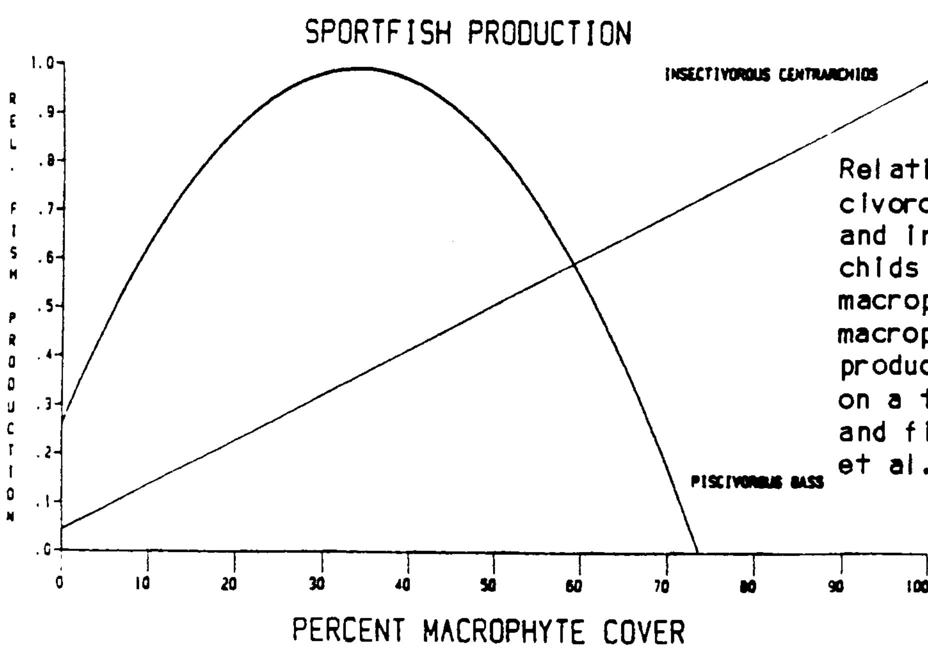
we give stocking rates for five types of plant communities commonly problematic in Illinois. These are the plant assemblages for which there is adequate data to make explicit recommendations (Table 1-1). We can provide only a generalized set of guidelines for other species until more data are available (Table 1-2).

(4) Site specific variables. There are a large number of other factors that vary from site to site or from year to year within sites that can influence the long-term performance of a particular stocking of grass carp. For example, factors that can influence annual variation in growth and regeneration rates of aquatic macrophytes include: competition from phytoplankton populations, nutrient loadings, and herbicides leaching from a surrounding watershed. Other factors can affect the longevity or vigor of the carp; abnormal weather may cause catastrophic mortality (winter or summer kills) or suppress feeding. High fishing pressure may reduce the number of carp below effective levels. None of these factors can be predicted for particular sites and yet may lead to variations in the results of a particular level of stocking. Because these site-specific variables cannot be controlled, our approach has been to ignore (or average out when possible) these types of variations. While correcting stocking rates for only predictable sources of variation may be incomplete, it is clearly superior to ignoring all sources of variation and making no corrections at all. It is important, therefore, that users of the recommendations below note that the results of stocking at suggested rates will undoubtedly vary somewhat from site to site. However, using these rates provides the best guarantee available that a planned grass carp stocking will be both cost-effective and ecologically safe.

STOCKING STRATEGIES

There are at least two basic approaches possible in stocking grass carp for biological control purposes: (1) serial stocking and (2) batch stocking, either of these strategies may be desirable in certain circumstances. In serial stocking, fish are stocked into a body of water at more or less regular, prescribed intervals (i.e., serially); the basic serial pattern is repeated as long as control is desired. Frequent stockings help minimize the number of fish required to achieve a specified level of control. The opposite strategy is taken in batch stocking. Here the principle is to stock as infrequently as possible, putting in fish in single large "batches" sized to compensate for the long periods between stockings. For most situations in Illinois, we recommend serial stocking. It is more efficient and cost effective, and it allows a greater degree of control over the amount of plant reduction to be achieved. We present stocking rate recommendations below using both serial and 10-year batch stocking strategies.

In using either of these strategies, the amount of plant control desired must be specified. Because aquatic plants are important in the trophic dynamics of most Illinois sport fisheries (Wiley et al. 1984) and in sediment stabilization (Wiley and Gorden 1984b, Chapter 4), total eradication of aquatic macrophytes is seldom desirable. Research on typical bass-bluegill communities suggests that 36-40% plant cover in littoral areas provides an optimal habitat for largemouth bass productivity (see below). We recommend that in most multiple-use waters this 40% plant



Relative production of piscivorous largemouth bass and insectivorous centrarchids as a function of macrophyte cover. Optimal macrophyte cover for bass production is 36-40%. Based on a trophic dynamic model and field data from Wiley et al. (1984).

cover value be used as a target level of control. To that end, we provide what will be termed a "best management practice" (BMP) stocking rate estimate for both serial and batch strategies. The BMP stocking rates are designed to reduce plant coverage to approximately 40% of the total littoral surface area. We also provide stocking recommendations for the "eradication" of all plants, although we caution against their use without a clear understanding of possible implications for sport fish production and alterations in water quality.

RECOMMENDATIONS

Methods and data tables necessary to calculate recommended stocking rates using both serial and batch stocking scenarios are provided below. These recommendations are for Illinois waters and assume the fish being stocked are sterile triploid grass carp. The stocking tables and curves used have been derived from extensive analyses and simulations using IHF3S. Because these tables summarize large amounts of data, they are necessarily very general in nature. By far the most accurate way to determine stocking rates necessary to achieve a specified level of control in a given body of water is to gather the necessary biological and physical data and to use those data in IHF3S simulation analyses (see Chapter 3).

Serial Stocking

Suggested stocking rates for BMP serial stocking are given in Tables 1-3A through 1-3E. Using these tables, one can estimate the stocking rates for a specific body of water by the following procedure:

1. Determine the annual maximum area (hectares or acres) of vegetated littoral zone:

$$A = (\% \text{ cover} * \text{lake surface area})/100 \qquad (1)$$

2. Determine the area of the littoral zone (roughly the area < 2 m deep):

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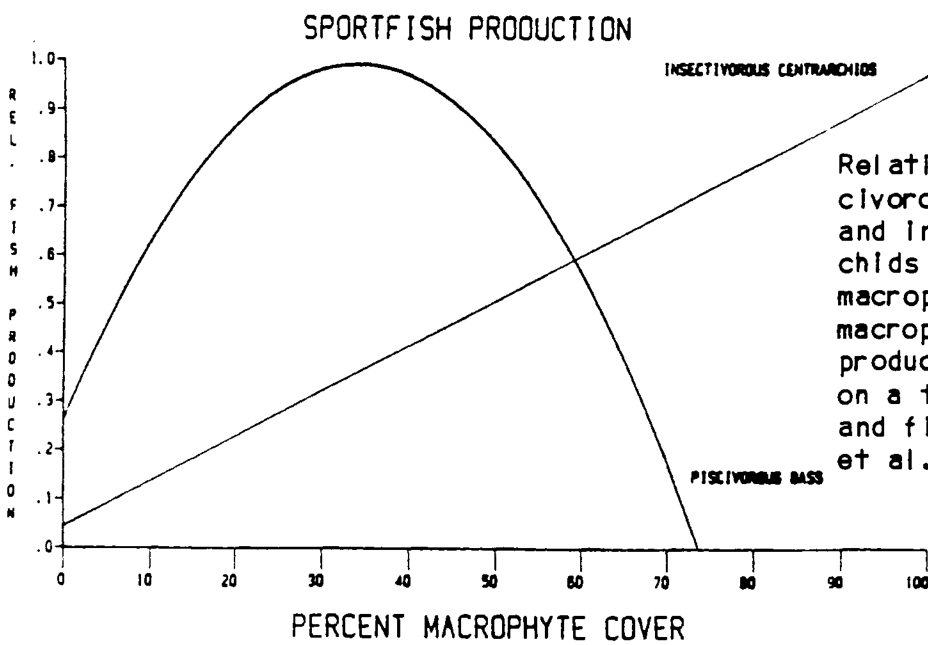

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1. Determine the annual maximum area (hectares or acres) of vegetated zone:

$$A = (\%\ \text{cover} * \text{lake surface area})/100 \qquad (1)$$

2. Determine the area of the littoral zone (roughly the area < 2 m deep):

$$L = (\% \text{ area} < 2 \text{ m} * \text{total lake area})/100 \tag{2}$$

[Note: A must not be larger than L]

3. Calculate the "area correction factor" (ACF):

$$ACF = A/L \tag{3}$$

[Note: ACF should never be > 1; if ACF $\leq$ 0.40, STOP, do NOT stock fish]

4. Find the appropriate table for the aquatic plant of interest and locate the climatic region of Illinois in which the stocking will occur. Read across the table to find the stocking rate per vegetated area for each year, the years to stock, and the optimal stocking size.

5. The actual number of fish to be stocked is then:

$$\text{number of fish} = \frac{\text{stocking rate in table} * A * ACF}{\text{average individual weight of fish}} \tag{4}$$

Make certain that all units are consistent, that is, either all metric (hectares, kilograms, and grams) or English (acres and pounds). Table 1-4 provides approximate conversions from length (inches and mm) to weight (pounds and grams) for both the triploid and diploid grass carp. Fish should be stocked as close to the optimal size listed as possible. Stocking should be done in the spring (April) of the years listed with the entire cycle repeated every 10 years.

Tables 1-5A through 1-5F provide serial stocking plans to achieve the eradication of all aquatic macrophytes in a particular body of water. These high rates of stocking should only be used with extreme care. The procedure for using these tables is similar but slightly different than that for the BMP tables:

1. Determine the annual maximum area (hectares or acres) of vegetated littoral zone:

$$A = (\% \text{ cover} * \text{total lake area})/100 \tag{5}$$

2. Find the appropriate table for the aquatic plant of interest and locate the climatic region of Illinois in which the stocking will occur. Read across the table to find the stocking rate per vegetated area for each year, the years to stock, and the optimal stocking size.

3. The actual number of fish to be stocked is then given by:

$$\text{number of fish} = \frac{\text{stocking rate in table} * A}{\text{average individual weight of fish}} \quad (6)$$

The two sets of serial stocking tables (Tables 1-3 and 1-5) given here provide rates to achieve approximately 60% and 100% reduction in plant cover. The area correction factor used in the BMP calculation adjusts the stocking rates to give a target plant coverage of approximately 40%. If some other percent cover target is desired (i.e., other than 40% or 0%), serial stocking rates should be determined using IHF3S simulations.

Batch Stocking

Stocking curves for a 10-year batch stocking program are given in Figs. 1-2 through 1-6. Each figure is a stocking curve for a particular plant community in climatic region 11. Table 1-6 contains correction factors to transfer stocking rates from the curves to all other regions in the state. To estimate the number of fish to be stocked under a best management practice scenario using a 10-year batch stocking strategy, use the following procedure:

1. Determine the annual maximum area (hectares or acres) of vegetated littoral zone:

$$A = (\% \text{ cover} * \text{total lake area})/100 \quad (7)$$

2. Determine the area of the littoral zone (roughly area < 2 m deep) (Note: A must not be larger than L):

$$L = (\% \text{ area} < 2 \text{ m} * \text{total lake area})/100 \quad (8)$$

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3. Calculate the "area correction factor" (ACF):

$$ACF = L/A \tag{3}$$

4. Find the appropriate table for the aquatic plant of interest and locate the climatic region of Illinois in which the stocking will occur. Read across the table to find the stocking rate per vegetated area for each year, the years to stock, and the optimal stocking size.

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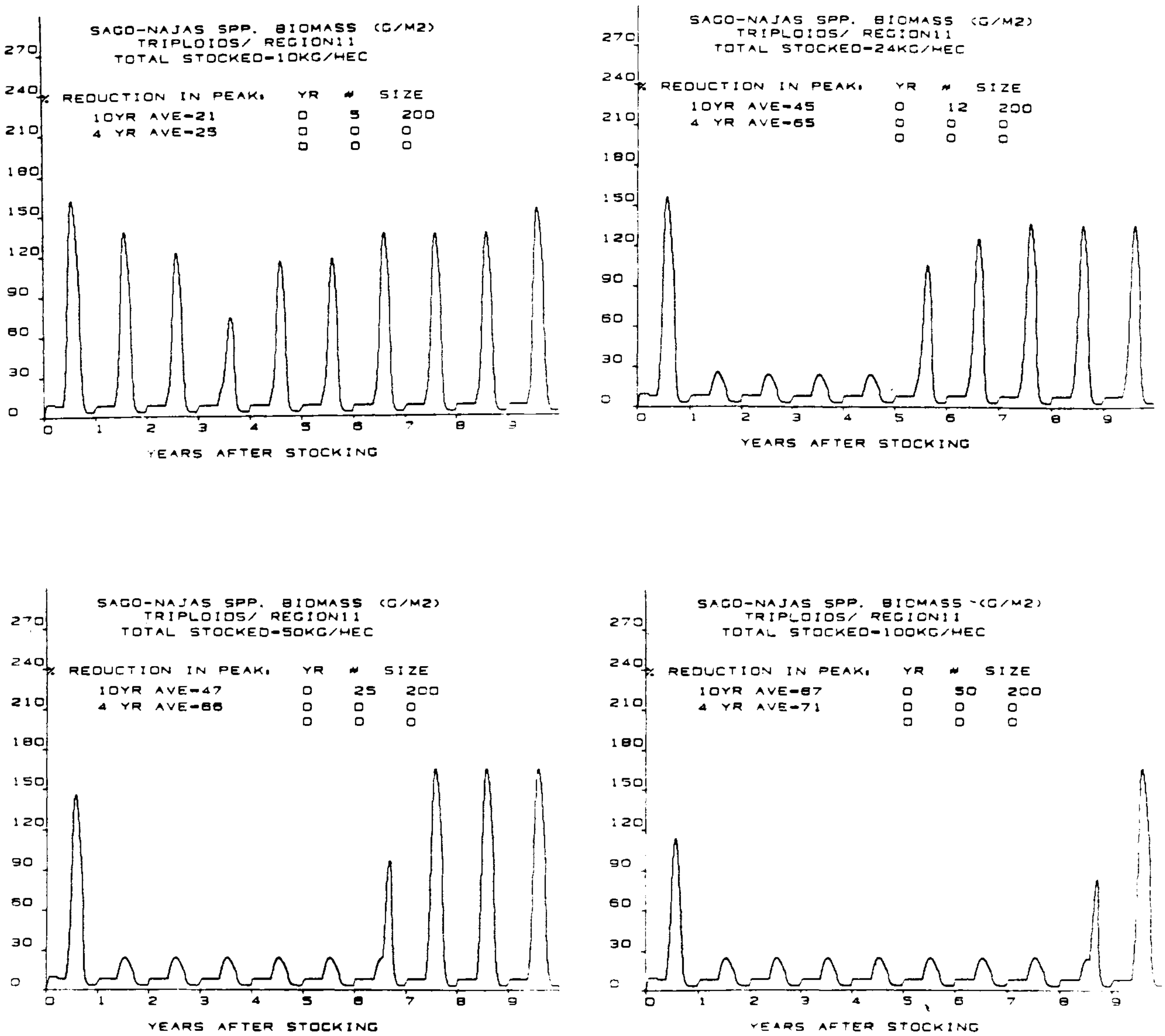
1. Determine the annual maximum area (hectares or acres) of vegetated littoral zone:

$$A = (\% \text{ cover} * \text{total lake area})/100 \tag{7}$$

2. Determine the area of the littoral zone (roughly area < 2 m deep) (Note: L must not be larger than A):

$$L = (\% \text{ area} < 2 \text{ m} * \text{total lake area})/100 \tag{8}$$

Examples of batch stocking strategy



Distribution of Potamogeton pectinatus/Najas spp. control over 10 years using batch stocking strategy. The level of control (g dry weight/m^2) is noted as percent reduction in peak biomass over a 4-year and a 10-year period for each stocking rate (10, 24, 50, and 100 kg/vegetated ha).

3. Calculate target % reduction T as:

$$T = 100 - [(40 - L)/A] \tag{9}$$

4. Find the appropriate curve and look up the stocking rate associated with the target % reduction T and the size of fish available.

5. Adjust the stocking rate for the climatic region of interest by multiplying the correction factor found in Table 1-6.

6. The number of fish to be stocked is given by:

$$\text{number of fish} = \frac{\text{stocking rate corrected for region} * A}{\text{average individual weight of fish}} \tag{10}$$

For maximum control using batch stocking (approaching eradication) omit steps 2 and 3, and set T = 100; the rest of the procedure is the same. These batch stocking rates will not give the target reduction each year but will average T over the 10-year period. The actual distribution of the plant control over that time period varies (see examples, p. 1-9). If performance early in the period is critical, stocking curves relating stocking density to average reduction during the first 4 years are available in Appendix 1.

The batch BMP stocking calculation above provides stocking rates sufficient to achieve a target of 40% plant cover. Batch stocking rates to achieve other target coverages can be calculated in a similar manner by substituting the desired percent coverage for the number "40" in Eq. 9 and then following the remaining procedures outlined above.

Table 1-1. Macrophyte communities for which stocking recommendations are given in Tables 1-3 and 1-5.

Macrophyte assemblages	Species included (common name)	Climatic region where the macrophytes are problematic[1]	Common chemical control	Success of chemical controls
Potamogeton pectinatus	*P. pectinatus* (sago pondweed)	1, 8, 12, 15	Diquat	good/fair
Najas spp.	*N. flexilis* (slender naiad)	4, 8, 11-12, 15-20[2]	Aquathol-K Diquat Aquazine	good/fair
	N. minor (brittle naiad)	9-12, 16-20		
Elodea canadensis	*E. canadensis* (American elodea or waterweed)	1, 2, 5, 8	Diquat Aquazine	good/poor
Ceratophyllum demersum	*C. demersum* (coontail)	1-5, 17, 19	Aquathol-K	good/fair
Myriophyllum spp.	*M. spicatum* (Eurasian water milfoil)	2, 3, 6, 8, 9, 10	Aquathol-K Aquazine Hydrothol-K	good/fair
	M. pinnatum (variable water milfoil)	2, 3, 6, 8, 9, 10		
	M. exalbescens (northern water milfoil	2, 3, 6, 8, 9, 10		
	M. heterophyllum (broadleaf water milfoil)	2, 3, 6, 8, 9, 10		
	M. verticillatum (whorled water milfoil)	2, 3, 6, 8, 9, 10		
Potamogeton crispus/ *Najas flexilis*	*P. crispus* (curlyleaf pondweed)	1, 2, 4, 12, 15, 17	Hydrothol-K Cutrine plus Aquathol-K	good/fair
	N. flexilis (slender naiad)	4, 8, 11, 14, 16-20	Aquathol-K Diquat Aquazine	good/poor

[1]See Wiley et al. (1983).
[2]*Najas flexilis* and *Najas guadalupensis* are often indistinguishable, so the regions where *N. guadalupensis* is problematic are reported for *N. flexilis* (Wiley et al. 1983).

Table 1-2. Macrophyte communities for which stocking recommendations are made. Under each community are listed common aquatic plants in Illinois for which similar stocking rates may be used. Plants listed are among those considered problematic in Illinois (Wiley et al. 1983).

Potamogeton pectinatus (sago pondweed)/ *Najas* spp. (naiads)	*Elodea canadensis* (American elodea)	*Ceratophyllum demersum* (coontail)	*Myriophyllum* spp. (water milfoil)	*Potamogeton crispus* (curlyleaf pondweed)/ *Najas flexilis* (slender naiad)
Algae	*Elodea nuttallii* (waterweed)	*Ceratophyllum echinatum* (prickly coontail)	*Ranunculus spp.* (water buttercup)	*Potamogeton illinoensis* (Illinois pondweed)
Potamogeton foliosus (leafy pondweed)	*Elodea densa* (dense waterweed)	*Polygonum fluitans* (water smartweed)	*Cabomba caroliniana* (fanwort)	*Potamogeton nodosus* (American pondweed)
Potamogeton pusillus (small pondweed)	*Elodea occidentalis* (common waterweed)	*Nuphar advena* (spatterdock)		*Potamogeton amplifolius* (large-leaf pondweed)
Najas guadalupensis (southern naiad)	*Chara* spp. (muskgrass)	*Nelumbo lutea* (American lotus)		*Jussiaea repens* (creeping water primrose)
Najas marina (spiny naiad)	*Nitella* sp. (nitella)	*Nymphaea tuberosa* (white water lily)		
Najas gracillima (bushy pondweed)				
Lemna spp. (duckweed)				
Zannichellia palustris (horned pondweed)				

Table 1-4. Length-weight relationship for grass carp in Illinois.

Total length (inches)	Weight (pounds)	Total length (mm)	Weight (g)
5.0	0.0389	127.0	17.7
5.5	0.0524	139.7	23.8
6.0	0.0688	152.4	31.3
6.5	0.8846	165.1	40.2
7.0	0.1100	177.8	50.7
7.5	0.1385	190.5	63.0
8.0	0.1695	203.2	77.1
8.5	0.2050	215.9	93.2
9.0	0.2452	228.6	111.5
9.5	0.2905	241.3	132.0
10.0	0.3411	254.0	155.1
10.5	0.3975	266.7	180.7
11.0	0.4599	279.4	209.0
11.5	0.5286	292.1	240.3
12.0	0.6040	304.8	274.5
12.5	0.6864	317.5	312.0
13.0	0.7761	330.2	352.8
13.5	0.8736	342.9	397.1
14.0	0.9790	355.6	445.0
14.5	1.0928	368.3	496.7
15.0	1.2152	381.0	552.4
15.5	1.3467	393.7	612.1
16.0	1.4876	406.4	676.2
16.5	1.6381	419.1	744.6
17.0	1.7988	431.8	817.6
17.5	1.9698	444.5	895.4
18.0	2.1516	457.2	978.0
18.5	2.3444	469.9	1065.6
19.0	2.5487	482.6	1158.5
19.5	2.7648	495.3	1256.7
20.0	2.9931	508.0	1360.5
20.5	3.2339	520.7	1469.9
21.0	3.4875	533.4	1585.2
21.5	3.7543	546.1	1706.5
22.0	4.0347	558.8	1834.0
22.5	4.3291	571.5	1967.8
23.0	4.6377	584.2	2108.0
23.5	4.9610	596.9	2255.0
24.0	5.2993	609.6	2408.8
24.5	5.6529	622.3	2569.5
25.0	6.0223	635.0	2737.4

SERIAL STOCKING TABLES

Best Management Practice Control

and

Eradication

Table 1-3A. Stocking recommendations for BMP control of *Potamogeton pectinatus/Najas* spp. in each climatic region of Illinois. Stocking scenarios are given in both metric (kg/vegetated ha) and English (lb/ vegetated acre) units.

	Metric Units				English Units			
Region	10-yr cumulative stocking rate (kg/v. ha)	Stocking years	kg/v. ha at each stocking	Optimal fish size at each stocking (g)	10-yr cumulative stocking rate (lb/v. a)	Stocking years	lb/v. a at each stocking	Optimal fish size at each stocking (lb)
1	40	0-5	20-20	200-200	36	0-5	18-18	0.44-0.44
2	41	0-5	21-20	200-200	37	0-5	19-18	0.44-0.44
3	36	0-5	20-16	200-200	32	0-5	18-14	0.44-0.44
4	36	0-5	20-16	200-200	32	0-5	18-14	0.44-0.44
5	34	0-5	20-14	200-200	30	0-5	18-12	0.44-0.44
6	36	0-5	20-16	200-200	32	0-5	18-14	0.44-0.44
7	36	0-5	20-16	200-200	32	0-5	18-14	0.44-0.44
8	36	0-5	20-16	200-200	32	0-5	18-14	0.44-0.44
9	50	0-5	30-20	200-200	45	0-5	27-18	0.44-0.44
10	50	0-5	30-20	200-200	45	0-5	27-18	0.44-0.44
11	34	0-5	20-14	200-200	30	0-5	18-12	0.44-0.44
12	50	0-5	30-20	200-200	45	0-5	27-18	0.44-0.44
13	50	0-5	30-20	200-200	45	0-5	27-18	0.44-0.44
14	50	0-5	30-20	200-200	45	0-5	27-18	0.44-0.44
15	50	0-5	30-20	200-200	45	0-5	27-18	0.44-0.44
16	37	0-4	21-16	200-200	33	0-4	19-14	0.44-0.44
17	50	0-5	30-20	200-200	45	0-5	27-18	0.44-0.44
18	37	0-4	21-16	200-200	33	0-4	19-14	0.44-0.44
19	36	0-4	20-16	200-200	32	0-4	18-14	0.44-0.44
20	37	0-4	21-16	200-200	33	0-4	19-14	0.44-0.44

Note: Rates given in this stocking table assumes a spring (April) stocking. Stocking in April is recommended because it is most cost effective. However if fall stocking is planned, multiply given rates by 1.5.

Table 1-3B. Stocking recommendations for BMP control of *Elodea canadensis* in each climatic region of Illinois. Stocking scenarios are given in both metric (kg/vegetated ha) and English (lb/vegetated acre) units.

	Metric Units				English Units			
Region	10-yr cumulative stocking rate (kg/v. ha)	Stocking years	kg/v. ha at each stocking	Optimal fish size at each stocking (g)	10-yr cumulative stocking rate (lb/v. a)	Stocking years	lb/v. a at each stocking	Optimal fish size at each stocking (lb)
1	48	0-4	18-30	50-200	43	0-4	16-27	0.11-0.44
2	48	0-4	18-30	50-200	43	0-4	16-27	0.11-0.44
3	45	0-5	15-30	50-200	40	0-5	13-27	0.11-0.44
4	45	0-5	15-30	50-200	40	0-5	13-27	0.11-0.44
5	45	0-4	15-30	50-200	40	0-4	13-27	0.11-0.44
6	45	0-5	15-30	50-200	40	0-5	13-27	0.11-0.44
7	45	0-5	15-30	50-200	40	0-5	13-27	0.11-0.44
8	45	0-5	15-30	50-200	40	0-5	13-27	0.11-0.44
9	54	0-5	14-40	50-200	48	0-5	12-36	0.11-0.44
10	52	0-5	13-39	50-200	46	0-5	11-35	0.11-0.44
11	45	0-4	15-30	50-200	40	0-4	13-27	0.11-0.44
12	53	0-5	13-40	50-200	47	0-5	11-36	0.11-0.44
13	52	0-5	13-39	50-200	46	0-5	11-35	0.11-0.44
14	52	0-5	13-39	50-200	46	0-5	11-35	0.11-0.44
15	53	0-5	13-40	50-200	47	0-5	11-36	0.11-0.44
16	51	0-5	14-37	50-200	46	0-5	13-33	0.11-0.44
17	54	0-5	13-41	50-200	48	0-5	11-37	0.11-0.44
18	51	0-5	14-37	50-200	46	0-5	13-33	0.11-0.44
19	55	0-5	15-40	50-200	49	0-5	13-36	0.11-0.44
20	52	0-5	14-38	50-200	46	0-5	12-34	0.11-0.44

Note: Rates given in this stocking table assumes a spring (April) stocking. Stocking in April is recommended because it is most cost effective. However if fall stocking is planned, multiply given rates by 1.5.

Table 1-3C. Stocking recommendations for BMP control of _Ceratophyllum demersum_ in each climatic region of Illinois. Stocking scenarios are given in both metric (kg/vegetated ha) and English (lb/vegetated acre) units.

	Metric Units				English Units			
Region	10-yr cumulative stocking rate (kg/v. ha)	Stocking years	kg/v. ha at each stocking	Optimal fish size at each stocking (g)	10-yr cumulative stocking rate (lb/v. a)	Stocking years	lb/v. a at each stocking	Optimal fish size at each stocking (lb)
1	100	0	100	200	89	0	89	0.44
2	99	0	99	200	88	0	88	0.44
3	86	0-7	43-43	200-200	77	0-7	38-39	0.44-0.44
4	87	0-7	43-44	200-200	78	0-7	38-39	0.44-0.44
5	79	0-7	39-40	200-200	70	0-7	35-35	0.44-0.44
6	88	0-7	44-44	200-200	79	0-7	39-40	0.44-0.44
7	86	0-7	43-43	200-200	77	0-7	38-39	0.44-0.44
8	87	0-7	43-44	200-200	78	0-7	38-39	0.44-0.44
9	87	0-7	39-48	200-200	78	0-7	35-43	0.44-0.44
10	94	0-7	42-52	200-200	84	0-7	37-47	0.44-0.44
11	80	0-7	40-40	200-200	71	0-7	35-36	0.44-0.44
12	91	0-7	41-50	200-200	81	0-7	36-45	0.44-0.44
13	92	0-7	41-51	200-200	82	0-7	37-45	0.44-0.44
14	92	0-7	41-51	200-200	82	0-7	37-45	0.44-0.44
15	90	0-7	40-50	200-200	80	0-7	36-44	0.44-0.44
16	69	0-7	35-34	200-200	62	0-7	31-31	0.44-0.44
17	87	0-7	39-48	200-200	78	0-7	35-43	0.44-0.44
18	68	0-7	34-34	200-200	61	0-7	30-31	0.44-0.44
19	60	0-7	30-30	200-200	54	0-7	27-27	0.44-0.44
20	66	0-7	33-33	200-200	59	0-7	29-30	0.44-0.44

Note: Rates given in this stocking table assumes a spring (April) stocking. Stocking in April is recommended because it is most cost effective. However if fall stocking is planned, multiply given rates by 2.0.

Table 1-3D. Stocking recommendations for BMP control of *Myriophyllum* spp. in each climatic region of Illinois. Stocking scenarios are given in both metric (kg/vegetated ha) and English (lb/vegetated acre) units.

	Metric Units				English Units			
Region	10-yr cumulative stocking rate (kg/v. ha)	Stocking years	kg/v. ha at each stocking	Optimal fish size at each stocking (g)	10-yr cumulative stocking rate (lb/v. a)	Stocking years	lb/v. a at each stocking	Optimal fish size at each stocking (lb)
1	210	0-7	130-80	200-200	187	0-7	116-71	0.44-0.44
2	191	0-7	115-76	200-200	170	0-7	102-68	0.44-0.44
3	134	0-7	72-62	200-200	120	0-7	64-56	0.44-0.44
4	143	0-7	76-67	200-200	128	0-7	68-60	0.44-0.44
5	107	0-7	88-19	200-200	95	0-7	78-17	0.44-0.44
6	150	0-7	80-70	200-200	134	0-7	71-63	0.44-0.44
7	136	0-7	73-63	200-200	121	0-7	65-56	0.44-0.44
8	143	0-7	76-67	200-200	128	0-7	68-60	0.44-0.44
9	119	0-7	69-50	200-200	106	0-7	61-45	0.44-0.44
10	124	0-7	73-51	200-200	111	0-7	65-46	0.44-0.44
11	110	0-7	90-20	200-200	98	0-7	80-18	0.44-0.44
12	121	0-7	71-50	200-200	108	0-7	63-45	0.44-0.44
13	122	0-7	71-51	200-200	109	0-7	63-46	0.44-0.44
14	122	0-7	71-51	200-200	109	0-7	63-46	0.44-0.44
15	120	0-7	70-50	200-200	107	0-7	62-45	0.44-0.44
16	109	0-7	46-63	200-200	97	0-7	41-56	0.44-0.44
17	119	0-7	69-50	200-200	106	0-7	61-45	0.44-0.44
18	110	0-7	46-64	200-200	98	0-7	41-57	0.44-0.44
19	120	0-7	50-70	200-200	107	0-7	45-62	0.44-0.44
20	112	0-7	47-65	200-200	100	0-7	42-58	0.44-0.44

Note: Rates given in this stocking table assumes a spring (April) stocking. Stocking in April is recommended because it is most cost effective. However if fall stocking is planned, multiply given rates by 2.0.

Table 1-3E. Stocking recommendations for BMP control of *Potamogeton crispus*/*Najas flexilis* in each climatic region of Illinois. Stocking scenarios are given in both metric (kg/vegetated ha) and English (lb/vegetated acre) units.

	Metric Units				English Units			
Region	10-yr cumulative stocking rate (kg/v. ha)	Stocking years	kg/v. ha at each stocking	Optimal fish size at each stocking (g)	10-yr cumulative stocking rate (lb/v. a)	Stocking years	lb/v. a at each stocking	Optimal fish size at each stocking (lb)
1	11	0-5	6-5	50-50	10	0-5	5-5	0.11-0.11
2	11	0-5	6-5	50-50	10	0-5	5-5	0.11-0.11
3	10	0-5	5-5	50-50	9	0-5	5-4	0.11-0.11
4	10	0-5	5-5	50-50	9	0-5	5-4	0.11-0.11
5	9	0-5	5-4	50-50	8	0-5	4-4	0.11-0.11
6	10	0-5	5-5	50-50	9	0-5	5-4	0.11-0.11
7	10	0-5	5-5	50-50	9	0-5	5-4	0.11-0.11
8	10	0-5	5-5	50-50	9	0-5	5-4	0.11-0.11
9	13	0-5	7-6	50-50	12	0-5	6-6	0.11-0.11
10	13	0-5	7-6	50-50	12	0-5	6-6	0.11-0.11
11	9	0-5	5-4	50-50	8	0-5	4-4	0.11-0.11
12	13	0-5	7-6	50-50	12	0-5	6-6	0.11-0.11
13	13	0-5	7-6	50-50	12	0-5	6-6	0.11-0.11
14	13	0-5	7-6	50-50	12	0-5	6-6	0.11-0.11
15	13	0-5	7-6	50-50	12	0-5	6-6	0.11-0.11
16	10	0-5	5-5	50-50	9	0-5	5-4	0.11-0.11
17	13	0-5	7-6	50-50	12	0-5	6-6	0.11-0.11
18	10	0-5	5-5	50-50	9	0-5	5-4	0.11-0.11
19	10	0-5	5-5	50-50	9	0-5	5-4	0.11-0.11
20	10	0-5	5-5	50-50	9	0-5	5-4	0.11-0.11

Note: Rates given in this stocking table assumes a spring (April) stocking. Stocking in April is recommended because it is most cost effective. However if fall stocking is planned, multiply given rates by 1.5.

Table 1-5A. Stocking recommendations for the eradication of *Potamogeton pectinatus/Najas* spp. In each climatic region of Illinois. Stocking scenarios are given in both metric (kg/vegetated ha) and English (lb/vegetated acre) units.

	Metric Units				English Units			
Region	10-yr cumulative stocking rate (kg/v. ha)	Stocking years	kg/v. ha at each stocking	Optimal fish size at each stocking (g)	10-yr cumulative stocking rate (lb/ v. a)	Stocking years	lb/v. a at each stocking	Optimal fish size at each stocking (lb)
1	143	0-7	63-80	50-200-200	128	0-7	56-72	0.11-0.44
2	146	0-7	64-82	50-200-200	130	0-7	57-73	0.11-0.44
3	152	0-6-8	51-81-20	50-200-200	136	0-6-8	46-72-18	0.11-0.44-0.44
4	151	0-6-8	51-80-20	50-200-200	135	0-6-8	46-72-18	0.11-0.44-0.44
5	140	0-6-8	50-50-40	50-200-200	125	0-6-8	45-45-35	0.11-0.44-0.44
6	150	0-6-8	50-80-20	50-200-200	134	0-6-8	45-71-18	0.11-0.44-0.44
7	152	0-6-8	51-81-20	50-200-200	136	0-6-8	46-72-18	0.11-0.44-0.44
8	151	0-6-8	51-80-20	50-200-200	135	0-6-8	46-71-18	0.11-0.44-0.44
9	162	0-6-7	62-80-20	50-200-200	145	0-6-7	55-72-18	0.11-0.44-0.44
10	163	0-6-7	63-80-20	50-200-200	145	0-6-7	56-71-18	0.11-0.44-0.44
11	140	0-6-8	50-50-40	50-200-200	125	0-6-8	45-45-35	0.11-0.44-0.44
12	163	0-6-7	63-80-20	50-200-200	145	0-6-7	56-71-18	0.11-0.44-0.44
13	163	0-6-7	63-80-20	50-200-200	145	0-6-7	56-71-18	0.11-0.44-0.44
14	163	0-6-7	63-80-20	50-200-200	145	0-6-7	56-71-18	0.11-0.44-0.44
15	163	0-6-7	63-80-20	50-200-200	145	0-6-7	56-71-18	0.11-0.44-0.44
16	147	0-5-7	44-62-41	50-200-200	131	0-5-7	39-55-37	0.11-0.44-0.44
17	163	0-6-7	63-80-20	50-200-200	145	0-6-7	56-71-18	0.11-0.44-0.44
18	147	0-5-7	44-62-41	50-200-200	131	0-5-7	39-55-37	0.11-0.44-0.44
19	143	0-5-7	43-60-40	50-200-200	128	0-5-7	38-54-36	0.11-0.44-0.44
20	146	0-5-7	44-61-41	50-200-200	130	0-5-7	39-54-37	0.11-0.44-0.44

Note: Rates given in this stocking table assumes a spring (April) stocking. Stocking in April is recommended because it is most cost effective. However if fall stocking is planned, multiply given rates by 1.5.

Table 1-5B. Stocking recommendations for the eradication of _Elodea canadensis_ in each climatic region of Illinois. Stocking scenarios are given in both metric (kg/vegetated ha) and English (lb/vegetated acre) units.

	Metric Units				English Units			
Region	10-yr cumulative stocking rate (kg/v. ha)	Stocking years	kg/v. ha at each stocking	Optimal fish size at each stocking (g)	10-yr cumulative stocking rate (lb/v. a)	Stocking years	lb/v. a at each stocking	Optimal fish size at each stocking (lb)
1	140	0-6-9	50-50-40	50-200-200	125	0-6-9	45-45-36	0.11-0.44-0.44
2	151	0-6-9	54-54-43	50-200-200	135	0-6-9	48-48-38	0.11-0.44-0.44
3	216	0-6-7	47-95-74	50-200-200	193	0-6-7	42-85-66	0.11-0.44-0.44
4	208	0-6-7	44-93-71	50-200-200	186	0-6-7	39-84-63	0.11-0.44-0.44
5	157	0-6-7	76-51-30	50-200-200	140	0-6-7	68-46-26	0.11-0.44-0.44
6	203	0-6-7	43-90-70	50-200-200	181	0-6-7	38-81-62	0.11-0.44-0.44
7	214	0-6-7	46-95-73	50-200-200	191	0-6-7	41-85-65	0.11-0.44-0.44
8	208	0-6-7	44-93-71	50-200-200	186	0-6-7	39-83-64	0.11-0.44-0.44
9	245	0-5	61-184	50-200	218	0-5	55-164	0.11-0.44
10	233	0-5	58-175	50-200	208	0-5	53-156	0.11-0.44
11	155	0-6-7	75-50-30	50-200-200	138	0-6-7	67-45-26	0.11-0.44-0.44
12	238	0-5	60-178	50-200	212	0-5	53-159	0.11-0.44
13	237	0-5	59-178	50-200	211	0-5	52-159	0.11-0.44
14	237	0-5	59-178	50-200	211	0-5	52-159	0.11-0.44
15	240	0-5	60-180	50-200	214	0-5	54-160	0.11-0.44
16	219	0-5	73-146	50-200	195	0-5	65-130	0.11-0.44
17	244	0-5	61-183	50-200	218	0-5	54-164	0.11-0.44
18	219	0-5	73-146	50-200	195	0-5	65-130	0.11-0.44
19	225	0-5	75-150	50-200	201	0-5	67-134	0.11-0.44
20	221	0-5	74-147	50-200	197	0-5	66-131	0.11-0.44

Note: Rates given in this stocking table assumes a spring (April) stocking. Stocking in April is recommended because it is most cost effective. However if fall stocking is planned, multiply given rates by 1.5.

Table 1-5C. Stocking recommendations for the eradication of _Ceratophyllum demersum_ in each climatic region of Illinois. Stocking scenarios are given in both metric (kg/vegetated ha) and English (lb/vegetated acre) units.

	Metric Units				English Units			
Region	10-yr cumulative stocking rate (kg/v. ha)	Stocking years	kg/v. ha at each stocking	Optimal fish size at each stocking (g)	10-yr cumulative stocking rate (lb/v. a)	Stocking years	lb/v. a at each stocking	Optimal fish size at each stocking (lb)
1	510	0	510	200	455	0	455	0.44
2	470	0	470	200	419	0	419	0.44
3	311	0-8	83-228	200-200	277	0-8	74-203	0.44-0.44
4	327	0-8	87-240	200-200	292	0-8	78-214	0.44-0.44
5	343	0-8	88-255	200-200	306	0-8	78-228	0.44-0.44
6	340	0-8	90-250	200-200	303	0-8	80-223	0.44-0.44
7	314	0-8	84-230	200-200	280	0-8	75-205	0.44-0.44
8	328	0-8	87-241	200-200	293	0-8	78-215	0.44-0.44
9	309	0-7	90-219	200-200	276	0-7	80-196	0.44-0.44
10	317	0-7	92-225	200-200	283	0-7	82-201	0.44-0.44
11	350	0-8	90-260	200-200	312	0-8	80-232	0.44-0.44
12	311	0-7	90-221	200-200	277	0-7	80-197	0.44-0.44
13	312	0-7	90-222	200-200	278	0-7	80-198	0.44-0.44
14	312	0-7	90-222	200-200	278	0-7	80-198	0.44-0.44
15	310	0-7	90-220	200-200	276	0-7	80-196	0.44-0.44
16	294	0-7-8	91-130-73	200-200-200	262	0-7-8	81-116-65	0.44-0.44-0.44
17	309	0-7	90-219	200-200	276	0-7	80-196	0.44-0.44
18	294	0-7-8	91-130-73	200-200	262	0-7-8	81-116-65	0.44-0.44-0.44
19	320	0-7-8	100-140-80	200-200-200	285	0-7-8	89-125-71	0.44-0.44-0.44
20	300	0-7-8	93-132-75	200-200-200	268	0-7-8	83-118-67	0.44-0.44-0.44

Note: Rates given in this stocking table assumes a spring (April) stocking. Stocking in April is recommended because it is most cost effective. However if fall stocking is planned, multiply given rates by 2.0.

Table 1-5D. Stocking recommendations for the eradication of <u>Myriophyllum</u> spp. in each climatic region of Illinois. Stocking scenarios are given in both metric (kg/vegetated ha) and English (lb/vegetated acre) units.

	Metric Units				English Units			
Region	10-yr cumulative stocking rate (kg/v. ha)	Stocking years	kg/v. ha at each stocking	Optimal fish size at each stocking (g)	10-yr cumulative stocking rate (lb/v. a)	Stocking years	lb/v. a at each stocking	Optimal fish size at each stocking (lb)
1	540	0-8	260-280	200-200	482	0-8	232-250	0.44-0.44
2	493	0-8	237-256	200-200	440	0-8	211-229	0.44-0.44
3	310	0-8	155-155	200-200	277	0-8	138-139	0.44-0.44
4	326	0-8	163-163	200-200	291	0-8	145-146	0.44-0.44
5	334	0-8	167-167	200-200	298	0-8	149-149	0.44-0.44
6	340	0-8	170-170	200-200	303	0-8	151-152	0.44-0.44
7	313	0-8	156-157	200-200	279	0-8	139-140	0.44-0.44
8	327	0-8	163-164	200-200	291	0-8	145-146	0.44-0.44
9	355	0-8	183-172	200-200	317	0-8	163-154	0.44-0.44
10	352	0-8	181-171	200-200	314	0-8	161-153	0.44-0.44
11	340	0-8	170-170	200-200	303	0-8	151-152	0.44-0.44
12	350	0-8	180-170	200-200	312	0-8	160-152	0.44-0.44
13	350	0-8	180-170	200-200	312	0-8	160-152	0.44-0.44
14	350	0-8	180-170	200-200	312	0-8	160-152	0.44-0.44
15	350	0-8	180-170	200-200	312	0-8	160-152	0.44-0.44
16	313	0	313	200	279	0	279	0.44
17	353	0-8	182-171	200-200	315	0-8	162-153	0.44-0.44
18	315	0	315	200	281	0	281	0.44
19	360	0	360	200	321	0	321	0.44
20	326	0	326	200	291	0	291	0.44

Note: Rates given in this stocking table assumes a spring (April) stocking. Stocking in April is recommended because it is most cost effective. However if fall stocking is planned, multiply given rates by 2.0.

Table 1-5E. Stocking recommendations for the eradication of _Potamogeton crispus_/_Najas flexilis_ in each climatic region of Illinois. Stocking scenarios are given in both metric (kg/vegetated ha) and English (lb/vegetated acre) units.

	Metric Units				English Units			
Region	10-yr cumulative stocking rate (kg/v. ha)	Stocking years	kg/v. ha at each stocking	Optimal fish size at each stocking (g)	10-yr cumulative stocking rate (lb/v. a)	Stocking years	lb/v. a at each stocking	Optimal fish size at each stocking (lb)
1	505	0-8-9	127-215-163	50-200-200	451	0-8-9	113-192-146	0.11-0.44-0.44
2	515	0-8-9	131-219-165	50-200-200	459	0-8-9	116-195-148	0.11-0.44-0.44
3	540	0-8-9	136-229-175	50-200-200	482	0-8-9	122-204-156	0.11-0.44-0.44
4	535	0-8-9	135-227-173	50-200-200	477	0-8-9	121-202-154	0.11-0.44-0.44
5	495	0-8-9	125-210-160	50-200-200	442	0-8-9	112-187-143	0.11-0.44-0.44
6	530	0-8-9	134-225-171	50-200-200	473	0-8-9	120-200-143	0.11-0.44-0.44
7	540	0-8-9	136-229-174	50-200-200	482	0-8-9	122-204-156	0.11-0.44-0.44
8	535	0-8-9	135-227-173	50-200-200	477	0-8-9	121-202-154	0.11-0.44-0.44
9	574	0-8-9	146-243-185	50-200-200	512	0-8-9	130-217-165	0.11-0.44-0.44
10	574	0-8-9	146-243-185	50-200-200	512	0-8-9	130-217-165	0.11-0.44-0.44
11	495	0-8-9	125-210-160	50-200-200	442	0-8-9	112-187-143	0.11-0.44-0.44
12	574	0-8-9	146-243-185	50-200-200	512	0-8-9	130-187-165	0.11-0.44-0.44
13	574	0-8-9	146-243-185	50-200-200	512	0-8-9	130-187-165	0.11-0.44-0.44
14	574	0-8-9	146-243-185	50-200-200	512	0-8-9	130-187-165	0.11-0.44-0.44
15	574	0-8-9	146-243-185	50-200-200	512	0-8-9	130-187-165	0.11-0.44-0.44
16	520	0-8-9	131-221-168	50-200-200	464	0-8-9	118-196-150	0.11-0.44-0.44
17	574	0-8-9	146-243-185	50-200-200	512	0-8-9	130-187-165	0.11-0.44-0.44
18	520	0-8-9	131-221-168	50-200-200	464	0-8-9	118-196-150	0.11-0.44-0.44
19	505	0-8-9	127-215-163	50-200-200	451	0-8-9	113-192-146	0.11-0.44-0.44
20	515	0-8-9	131-219-165	50-200-200	459	0-8-9	116-195-148	0.11-0.44-0.44

Note: Rates given in this stocking table assumes a spring (April) stocking. Stocking in April is recommended because it is most cost effective. However if fall stocking is planned, multiply given rates by 1.5.

TEN-YEAR BATCH STOCKING CURVES
AND
CLIMATIC REGION MULTIPLIERS

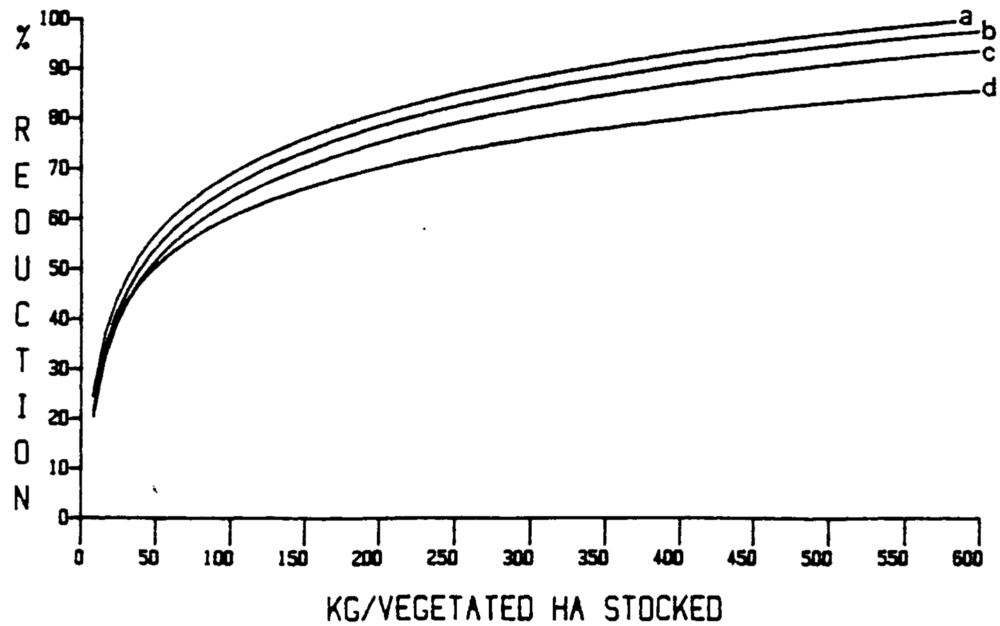


Figure 1-2. Stocking curves for *Potamogeton pectinatus*/ *Najas* spp. in Region 11 using 10-year batch stocking strategy. Simulations included four sizes of triploid grass carp: a = 50 g, b = 100 g, c = 200 g, and d = 400 g.

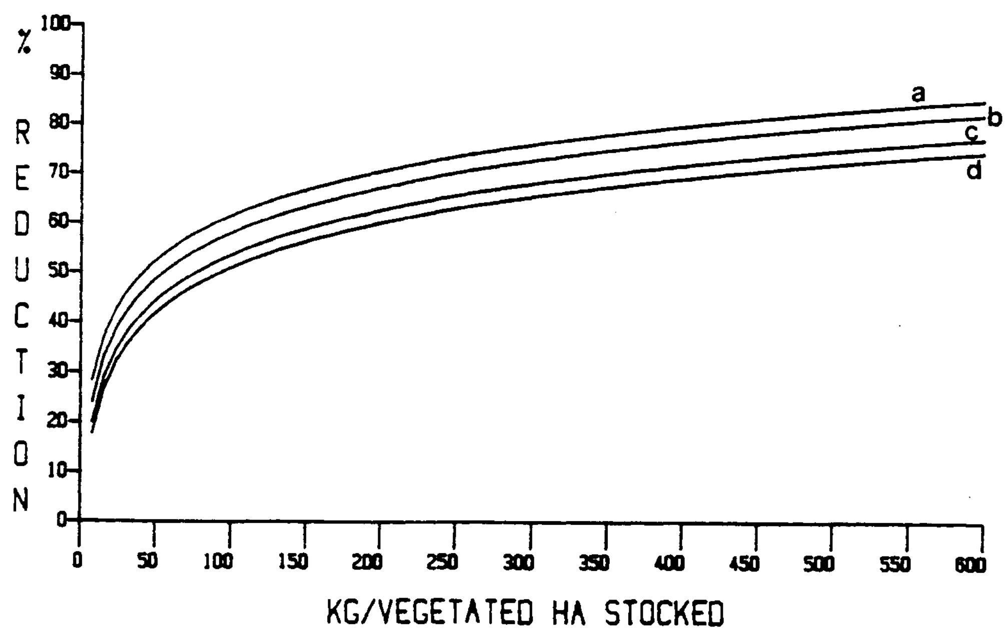


Figure 1-3. Stocking curves for *Elodea canadensis* in Region 11 using 10-year batch stocking strategy. Simulations included four sizes of triploid grass carp: a = 50 g, b = 100 g, c = 200 g, and d = 400 g.

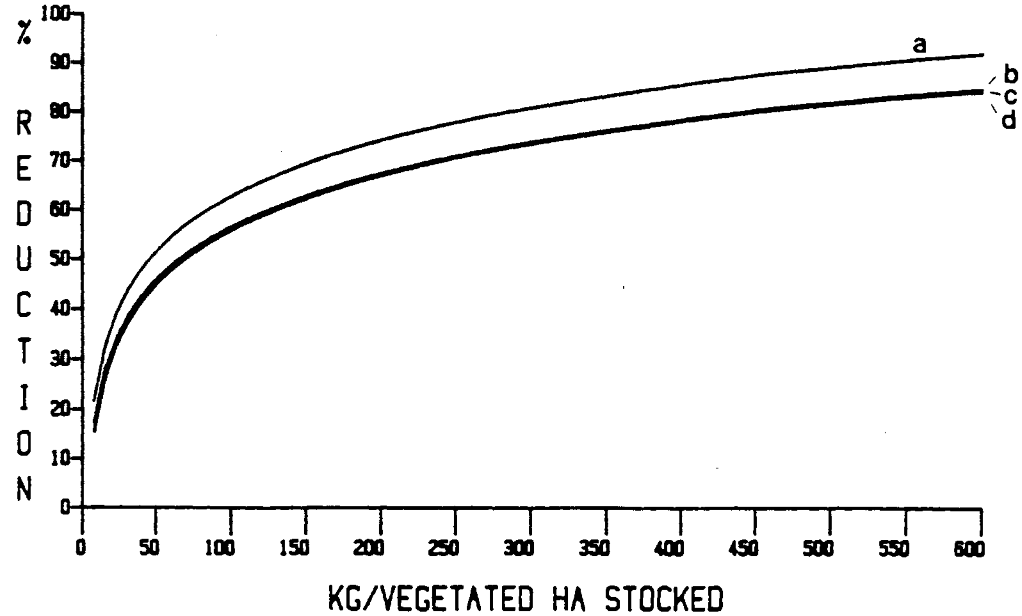


Figure 1-4. Stocking curves for Ceratophyllum demersum in Region 11 using 10-year batch stocking strategy. Simulations included four sizes of triploid grass carp: a = 50 g, b = 100 g, c = 200 g, and d = 400 g.

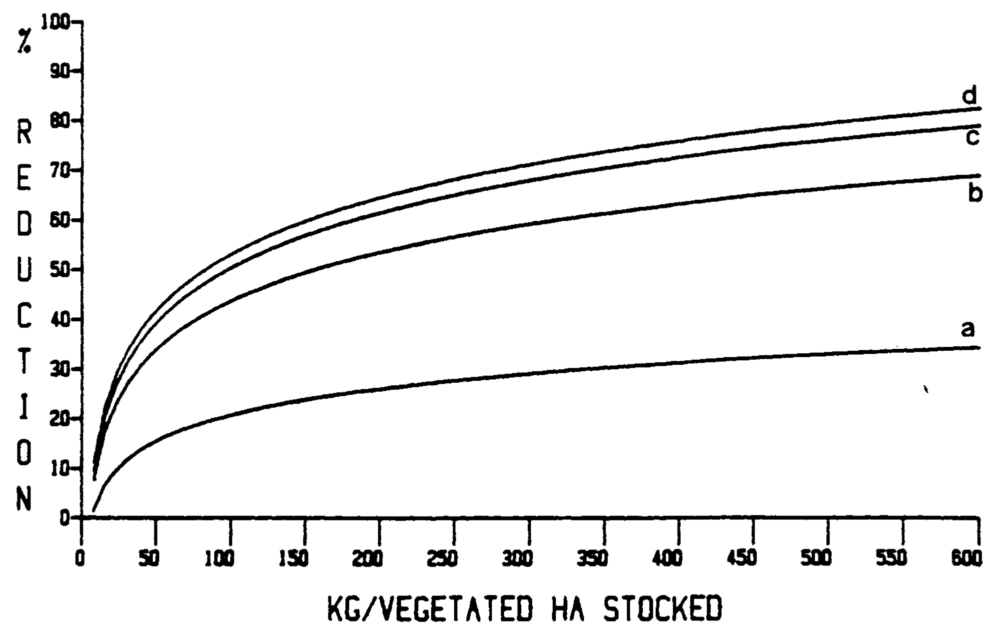


Figure 1-5. Stocking curves for Myriophyllum spp. in Region 11 using 10-year batch stocking strategy. Simulations included four sizes of triploid grass carp: a = 50 g, b = 100 g, c = 200 g, and d = 400 g.

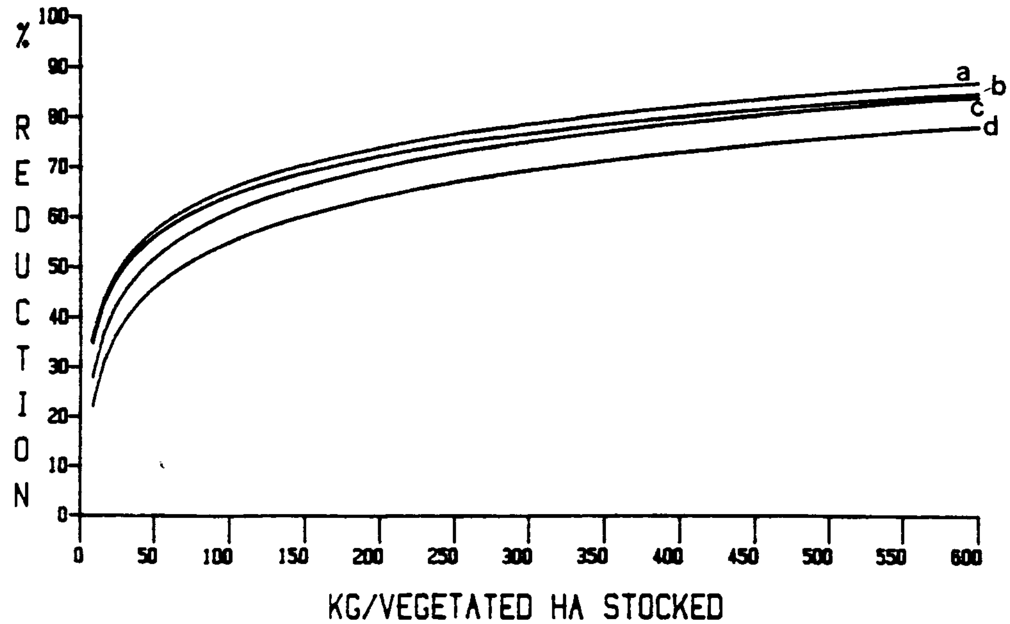


Figure 1-6. Stocking curves for <u>Potamogeton crispus</u>/ <u>Najas flexilis</u> in Region 11 using 10-year batch stocking strategy. Simulations included four sizes of triploid grass carp: a = 50 g, b = 100 g, c = 200 g, and d = 400 g.

Table 1-6. Regional multipliers for use with batch stocking rates to determine appropriate batch stocking rates for five macrophyte assemblages in each climatic region of Illinois. Multipliers are given for two control scenarios, best management practice and eradication. These calculations assume spring (April) stocking. If fall stocking is planned, rates for *Potamogeton pectinatus*/*Najas* spp., *Elodea canadensis*, and *P. crispus*/*N. flexilis* must be multiplied by 1.5; and rates for *Ceratophyllum demersum* and *Myriophyllum* spp. must be multiplied by 2.0.

Region	*Potamogeton pectinatus*/ *Najas* spp.	*Elodea canadensis*	*Ceratophyllum demersum*	*Myriophyllum* spp.	*Potamogeton crispus*/*Najas flexilis*
			Best Management Practice		
1	1.17	1.07	1.25	1.91	1.17
2	1.20	1.07	1.24	1.74	1.20
3	1.06	1.00	1.08	1.22	1.06
4	1.06	1.00	1.09	1.30	1.06
5	1.00	1.00	0.99	0.97	1.00
6	1.06	1.00	1.10	1.37	1.06
7	1.06	1.00	1.08	1.24	1.06
8	1.06	1.00	1.09	1.30	1.06
9	1.47	1.20	1.09	1.08	1.47
10	1.47	1.16	1.18	1.13	1.47
11	1.00	1.00	1.00	1.00	1.00
12	1.47	1.18	1.14	1.10	1.47
13	1.47	1.16	1.15	1.11	1.47
14	1.47	1.16	1.15	1.11	1.47
15	1.47	1.18	1.13	1.09	1.47
16	1.09	1.13	0.86	0.99	1.09
17	1.47	1.20	1.09	1.08	1.47
18	1.09	1.13	0.85	1.00	1.09
19	1.06	1.22	0.75	1.09	1.06
20	1.09	1.16	0.82	1.02	1.09
			Eradication		
1	1.02	0.90	1.46	1.59	1.02
2	1.04	0.97	1.34	1.45	1.04
3	1.09	1.39	0.89	0.91	1.09
4	1.08	1.34	0.93	0.96	1.08
5	1.00	1.01	0.98	0.98	1.00
6	1.07	1.31	0.97	1.00	1.07
7	1.09	1.38	0.90	0.92	1.09
8	1.08	1.34	0.94	0.96	1.08
9	1.16	1.58	0.88	1.04	1.16
10	1.16	1.50	0.91	1.03	1.16
11	1.00	1.00	1.00	1.00	1.00
12	1.16	1.54	0.89	1.03	1.16
13	1.16	1.53	0.89	1.03	1.16
14	1.16	1.53	0.89	1.03	1.16
15	1.16	1.55	0.89	1.03	1.16
16	1.05	1.41	0.84	0.92	1.05
17	1.16	1.57	0.88	1.04	1.16
18	1.05	1.41	0.84	0.93	1.05
19	1.02	1.45	0.91	1.06	1.02
20	1.04	1.43	0.86	0.96	1.04

Chapter 2

DISCUSSION OF STOCKING SIMULATIONS

In this chapter we briefly discuss the computer simulations upon which the stocking recommendations in this report were based. Over 1000 simulations of serial and batch stockings were run using IHF3S, a stocking simulation model developed at the Illinois Natural History Survey. Using computer simulations, we examined the effects of a number of key variables on the relationship between stocking density and amount of plant control achieved. The principal variables of interest included: climatic region (see Chapter 1), macrophyte community composition, and stocking strategy (batch versus serial). Summaries of results are presented below, organized by climatic region and by plant community.

CLIMATIC REGION II

Potamogeton pectinatus/*Najas* spp.

Three macrophyte species are included in this community, *Potamogeton pectinatus*, *Najas flexilis* and *Najas minor*. Their similar seasonal biomass phenologies and frequent co-habitation of Illinois ponds and lakes provided the basis for combining them into a single macrophyte assemblage in stocking simulation analyses. *Najas* spp. are among the most preferred food items of the carp and *P. pectinatus* is moderately palatable (Wiley and Gorden 1984b).

Results of batch simulations of carp feeding on *Potamogeton pectinatus*/*Najas* spp. showed that reasonable control could be achieved with low to moderate stocking rates. Batch stocking rates as low as 10 kg/vegetated ha yielded a 30-36% reduction in peak biomass over 10 years and 25 kg/vegetated ha a 50-60% reduction (Table 2-1). Up to 6 years of consecutive control of *P. pectinatus*/*Najas* spp. was possible by stocking 25 kg/vegetated ha (Table 2-2). Small carp (50-100 g) were generally more effective in long-term control (10 years) than larger fish (200-400 g) (Table 2-1).

In serial stocking simulations, Potamogeton pectinatus/Najas spp. generally required the lowest stocking levels of any plant community (Table 2-3). Over a 10-year period, the BMP scenario required 34 kg/vegetated ha in two stockings. Furthermore, only 140 kg/vegetated ha was needed to eradicate the macrophytes (Figs. 2-1 and 2-2). In the BMP scenario, carp stockings produced a "pulsing effect" characterized by long-term but low-amplitude oscillations of the plant populations. This pattern of alternating good and poor periods of plant production was an interesting by-product of BMP strategies in this and most other plant communities we examined. An interesting question arises as to whether or not this type of plant management strategy could have positive effects on the size structure of bass-sunfish populations by forcing alternating periods of heavy recruitment (dense plant populations) and high mortality (low plant levels). The result might be described as energetic "pumping" in which prey species are first produced and then fed to predator populations.

Elodea canadensis

Elodea canadensis poses problems through overabundant growth primarily over the northern and north-central portions of Illinois (including Region 11) and success of chemical control varies from good to poor. E. canadensis is moderately palatable to the grass carp (Wiley et al. 1983, Wiley and Gorden 1984b, Chapter 2).

As with Potamogeton pectinatus/Najas spp., batch stocking simulations resulted in better long-term control when smaller carp were used. A long-term control level of 60% reduction (BMP scenario) was attained at the 100 kg/vegetated ha stocking level and 5 consecutive years of control was achieved at a rate of 50 kg/vegetated ha (Tables 2-1 and 2-2). Relative to P. pectinatus/Najas spp., Elodea required only slightly higher batch stocking rates to achieve equivalent control (Table 2-1, Fig. 2-3). Using the serial stocking strategy, Elodea required 45 kg/vegetated ha (two stockings) for BMP and 155 kg/ha (three stockings) for eradication (Table 2-3, Figs. 2-4 and 2-5). Again, these stocking rates were only slightly higher than those needed for equivalent control of _P. pectinatus_/_Najas_ spp. (Table 2-3).

Ceratophyllum demersum

Ceratophyllum demersum is one of the most problematic aquatic plants in Illinois. It is troublesome over at least 67% of the state and is controlled chemically with only fair success. _Ceratophyllum_ is one of the plant species least preferred by grass carp (Wiley and Gorden 1984b, Chapter 2).

In batch simulations, 5 or more years of consecutive control was achieved at 50 kg/vegetated ha (Table 2-2). To achieve the 10-year average control level of 60% used in our BMP scenario, a batch stocking rate of 100 kg/vegetated ha was required. This is a rate twice that required for _Potamogeton crispus_/_Najas flexilis_ (Table 2-1). Using smaller fish provided only a slight advantage in control at low stocking rates (Table 2-1). Paired data from batch simulations were used to compare control requirements of _P. pectinatus_/_Najas_ spp. with those of _Ceratophyllum demersum_ (Fig. 2-6). At moderate control levels, a much higher stocking rate of carp was needed to control _C. demersum_. Only at very high control levels could similar stocking rates be used for these two macrophyte assemblages.

Using serial stocking, BMP and eradication scenarios with _Ceratophyllum demersum_ required 80 kg/vegetated ha and 350 kg/vegetated ha, respectively (Figs. 2-7 and 2-8, Table 2-3). These rates are twice those required for either of the two previously discussed macrophyte assemblages.

Myriophyllum spp.

Myriophyllum spp. are also very troublesome plants in Illinois. They grow and spread rapidly and are considered difficult to control with chemicals.

And like Ceratophyllum demersum, these plants are relatively unpalatable to grass carp (Wiley and Gorden 1984b, Chapter 2).

In batch simulations, larger carp achieved markedly better control with Myriophyllum spp. than did small carp regardless of stocking rate. BMP control levels were achieved at 100 kg/vegetated ha, but only with large fish (Table 2-1). This reversal of the fish size vs. achieved control relationship was unique to Myriophyllum spp. Larger carp (400 g) at 100 kg/vegetated ha were required to attain 5 or more consecutive years of control. With small carp (50 g) the same control required twice that amount (Table 2-2). A plot of paired control levels showed that substantially higher stocking rates were needed to control Myriophyllum spp. than Potamogeton pectinatus/Najas spp., particularly at moderate control levels (Fig. 2-9).

Serial stocking rates of 110 and 340 kg/vegetated ha were required to achieve BMP and eradication control levels, respectively. Those rates are 2.5 to more than 3 times the rates needed to achieve comparable control of P. pectinatus/Najas spp. communities (Figs. 2-10 and 2-11, Table 2-3).

Potamogeton crispus/Najas flexilis

Potamogeton crispus and Najas flexilis frequently inhabit the INHS experimental ponds used for field trials on this project. P. crispus is a spring (cool water) perennial species and N. flexilis is a summer annual species. Peak biomass of the important cohorts of each species coincides with low biomass levels of the other producing a temporal segregation resulting in frequent occurrence in aquatic systems of Illinois.

Results of batch simulations indicated that very low stocking rates could achieve moderate levels of control of this assemblage. As with Potamogeton pectinatus/Najas spp., smaller carp (50-100 g) achieved greater long-term control at low to moderate stocking rates. At higher rates (100-500 kg/vegetated ha), similar control was achieved regardless of carp size (Table 2-1). An average reduction in peak biomass of 60% (BMP level control) with batch stocking was achieved with 50 kg/vegetated ha. Two consecutive years of control were achieved using as little as 5 kg/vegetated ha of small carp; however 5 or more consecutive years of control required 50 kg/vegetated ha, an amount twice that required for P. pectinatus/Najas spp. (Table 2-2). A comparison of P. crispus/N. flexilis and P. pectinatus/Najas spp. using paired batch control levels showed that moderate control of the former required lower stocking rates than P. pectinatus/Najas spp., but reductions of 60% or more required markedly higher stocking rates than for P. crispus/N. flexilis (Fig. 2-12).

Using serial stocking strategies Potamogeton crispus/Najas flexilis required only 9 kg/vegetated ha for BMP level control (Table 2-3, Fig. 2-13). The BMP control scenario for P. crispus/N. flexilis was the only time that fewer carp (75% fewer) achieved better control than with P. pectinatus/Najas spp. P. crispus, as a cool water species, is available to the carp for early spring feeding. This allows for added fish growth that is not possible in the absence of cool water species in Illinois. This additional early season growth is responsible for improved control in subsequent years.

Conversely, Potamogeton crispus/Najas flexilis required about 3.5 times the stocking rate of P. pectinatus/Najas spp. for eradication (Table 2-3, Fig. 2-14). Early growth of spring species may also be a factor contributing to the very high stocking rates necessary to eradicate this plant community. Because P. crispus maintains aboveground overwintering biomass and growth is initiated early in the spring, populations are well established when the carp begin to feed. This 'head start' that the macrophytes have may make peak biomass, which occurs at relatively low temperatures, difficult to eradicate. In addition, P. crispus is only moderately preferred by the carp, and the combination of relatively low temperatures and inherently slow feeding rates make eradication even more difficult.

OTHER CLIMATIC REGIONS

Sets of serial stocking simulations of each plant population except Potamogeton crispus/Najas flexilis were run for Regions 1, 6, 15, and 19 (Table 2-3). Results of those simulations indicated that different plant assemblages had different patterns of response to climatic variation in Illinois. P. pectinatus/Najas spp. required similar stocking rates for achievement of both control scenarios in all temperature regions, although region 15 rates were slightly higher than the others (Table 2-3 , Figs. 2-15 through 2-22). Elodea canadensis required rates most similar to P. pectinatus/Najas spp. in all regions. However, with E. canadensis there was a trend toward increased rates in warmer climatic regions (Table 2-3, Figs. 2-23 through 2-30).

Ceratophyllum demersum routinely required at least twice as many carp as Potamogeton pectinatus/Najas spp. for BMP control and up to 3.5 times as many carp were needed for eradication of C. demersum. Cooler climatic regions required increased stocking rates for control of C. demersum; region 1 requiring as much as 80% more fish than other regions (Table 2-3, Figs. 2-31 through 2-38). Myriophyllum spp. required the highest stocking rates of all the macrophyte communities (Table 2-3, Figs. 2-39 through 2-46). Often three times, and in some instances as many as five times, as many carp were needed for equivalent control of Myriophyllum spp. as for P. pectinatus/Najas spp. As temperature decreased, increased stocking rates were needed for BMP control and eradication of Myriophyllum spp., a trend similar to that seen with C. demersum.

Serial stocking rates from simulations in the five climatic regions were analyzed with the mean regional growing season temperature to develop a relationship between climatic variation and stocking rate (Table 2-4). This analysis provided the basis for extrapolation of BMP and eradication stocking rates in those five regions to all other climatic regions of the state. The climatic regions were clustered into 5 groups according to their mean growing season temperature and stocking rate for each region within the group was estimated based on the simulated region stocking rate.

Stocking rates in kg/vegetated ha and lb/vegetated acre for BMP and eradication in each temperature region are given in Tables 1-3A through 1-3E and 1-5A through 1-5E.

Once established, the stocking rate in each climatic region was then compared with the rate in Region 11. The resulting regional relationship (multiplier) has been used in our stocking recommendations to determine the appropriate batch stocking rate for each macrophyte assemblage in all climatic regions outside region 11 (Table 1-6, Figs. 1-2 through 1-6)

Table 2-1. Simulated long-term (10-year) control of five macrophyte communities by triploid grass carp using a batch stocking strategy. Control is expressed as percent reduction in peak biomass.

Macrophyte	Stocking rate (kg/vegetated ha)	Control (%) Fish size at stocking (g) 50	100	200	400
Potamogeton pectinatus/ _Najas_ spp.	5	20	17	9	10
	10	36	30	22	21
	25	60	54	47	42
	50	53	57	61	61
	100	65	64	67	65
	200	73	76	70	69
	500	78	79	75	74
Elodea canadensis	5	17	11	6	5
	10	30	20	17	13
	25	51	46	34	28
	50	58	54	49	46
	100	61	60	57	55
	200	70	66	65	64
	500	77	76	72	71
Ceratophyllum demersum	5	3	2	1	1
	10	7	5	4	4
	25	47	27	14	14
	50	60	58	55	56
	100	68	67	66	66
	200	75	75	71	71
	500	86	88	83	82
Myriophyllum spp.	5	0	0	0	1
	10	0	1	1	2
	25	1	4	5	7
	50	2	11	17	23
	100	6	48	61	67
	200	19	68	76	79
	500	64	79	87	87
Potamogeton crispus/ _Najas flexilis_	5	32	27	19	12
	10	42	32	33	29
	25	50	48	47	32
	50	66	58	52	41
	100	73	68	61	52
	200	76	71	69	69
	500	69	78	80	79

Table 2-2. Simulated years of consecutive control (greater than 80% reduction in peak biomass) achieved by batch stocking of triploid grass carp in climatic Region 11. Simulation results for five macrophyte assemblages are presented.

Macrophyte	Stocking rate (kg/vegetated ha)	Consecutive years of control: Fish size at stocking (g) 50	100	200	400
Potamogeton pectinatus/ Najas spp.	5	0	0	0	0
	10	1	0	0	0
	25	6	5	4	2
	50	6	5	6	6
	100	6	6	7	6
	200	7	8	7	7
	500	8	8	8	8
Elodea canadensis	5	0	0	0	0
	10	1	0	0	0
	25	4	1	1	0
	50	5	5	3	1
	100	6	5	5	5
	200	6	6	6	5
	500	8	8	7	7
Ceratophyllum demersum	5	0	0	0	0
	10	0	0	0	0
	25	4	0	0	0
	50	6	6	5	5
	100	7	7	7	7
	200	8	8	7	7
	500	9	10	9	9
Myriophyllum spp.	5	0	0	0	0
	10	0	0	0	0
	25	0	0	0	0
	50	0	0	0	0
	100	0	3	4	6
	200	0	6	7	7
	500	5	7	8	8
Potamogeton crispus/ Najas flexilis	5	2	1	0	0
	10	3	2	1	1
	25	4	3	2	2
	50	5	5	4	3
	100	6	6	5	4
	200	7	7	6	6
	500	5	7	7	7

Table 2-3. Stocking rates (kg/vegetated ha) of triploid grass carp used in simulations to achieve two serial stocking control scenarios in five climatic regions in Illinois. BMP = best management practices and ER = eradication.

Climatic region	*Potamogeton pectinatus/ Najas* spp.		*Elodea canadensis*		*Ceratophyllum demersum*		*Myriophyllum* spp.		*Potamogeton crispus/ Najas flexilis*	
	BMP	ER	BMP	ER	BMP	ER	BMP	ER	BMP	ER
1	40	143	48	140	100	510	210	540	--	--
6	36	150	45	203	88	340	150	340	--	--
11	34	140	45	155	80	350	110	340	9	495
15	50	163	53	240	90	310	120	350	--	--
19	36	143	55	225	60	320	120	360	--	--

-- no simulation

Table 2-4. Mean growing season temperature in 20 climatic regions designated by the Illinois State Water Survey.

Climatic region	Mean temperature (°C)
1	19.45
2	19.75
3	20.89
4	20.65
5	21.35
6	20.48
7	20.84
8	20.64
9	22.43
10	21.80
11	21.22
12	22.05
13	21.98
14	21.98
15	22.15
16	22.72
17	22.37
18	22.77
19	23.48
20	23.00

BI-VARIATE PLOTS FROM BATCH SIMULATIONS, USING EQUIVALENT STOCKING RATES, COMPARING CONTROL LEVELS ACHIEVED IN DIFFERENT PLANT COMMUNITIES

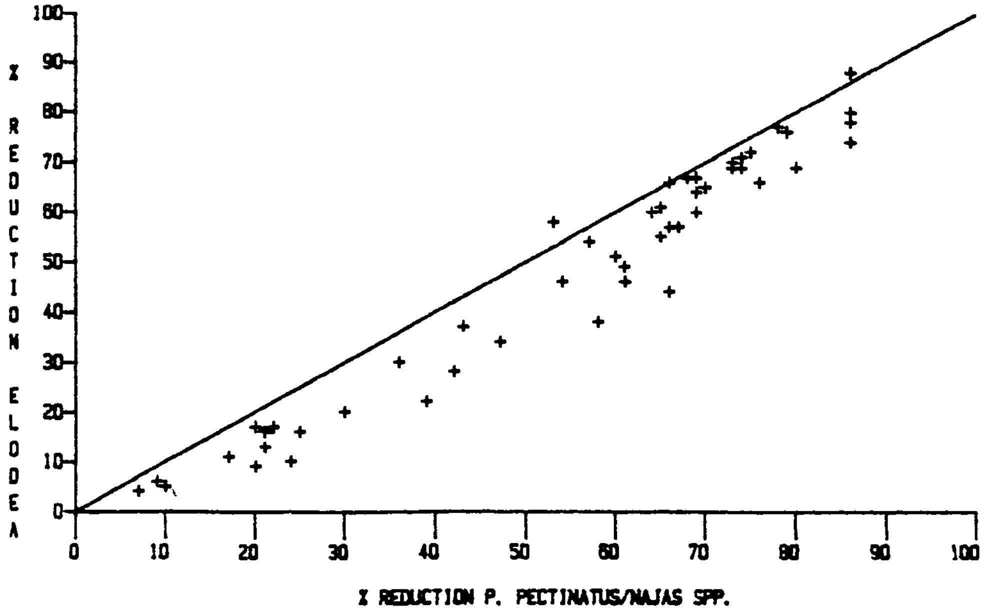


Fig. 2-3. Control at equivalent stocking rates (as percent reduction in peak biomass) for Potamogeton pectinatus/Najas spp. and Elodea canadensis. The line represents equal control in the two macrophyte assemblages.

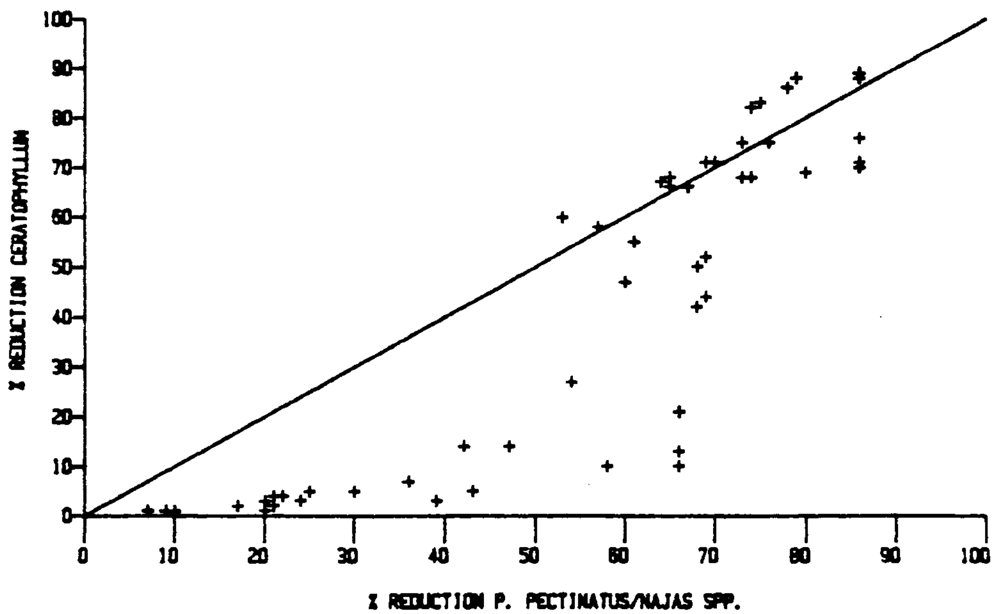


Fig. 2-6. Control at equivalent stocking rates (as percent reduction in peak biomass) for Potamogeton pectinatus/Najas spp. and Ceratophyllum demersum. The line represents equal control in the two macrophyte assemblages.

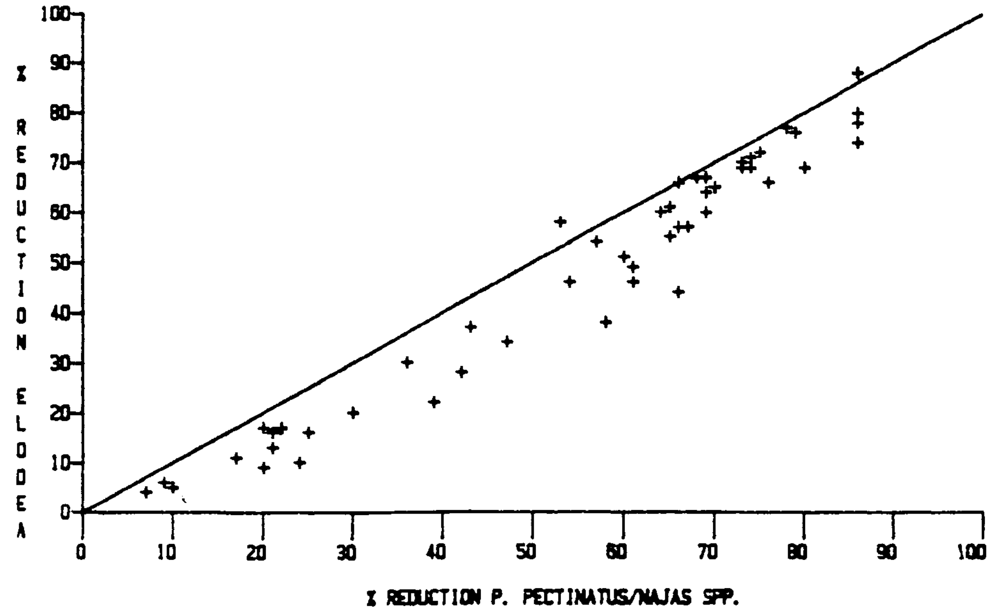


Fig. 2-3. Control at equivalent stocking rates (as percent reduction in peak biomass) for Potamogeton pectinatus/Najas spp. and Elodea canadensis. The line represents equal control in the two macrophyte assemblages.

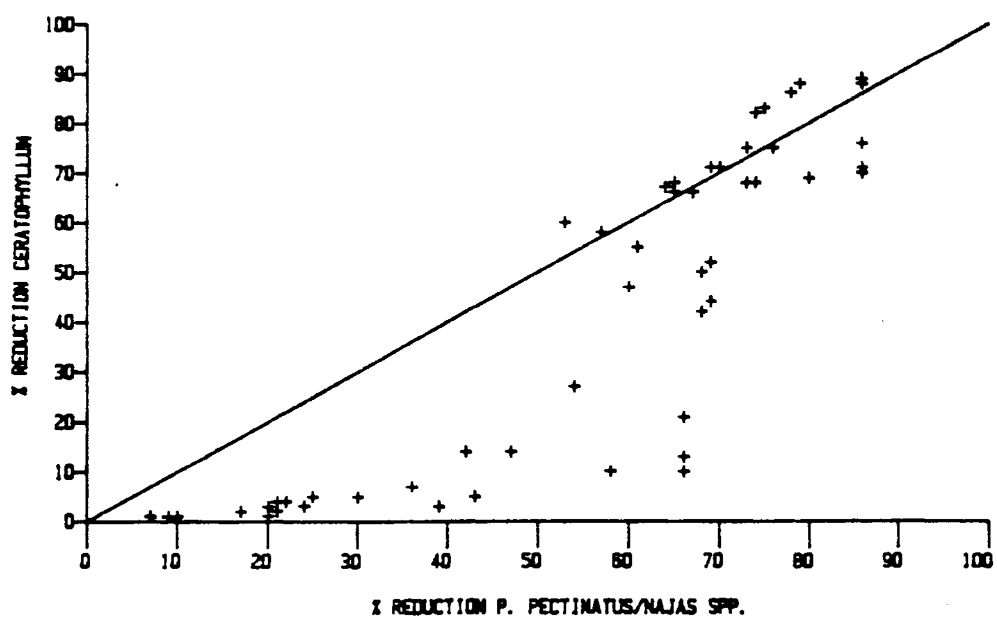


Fig. 2-6. Control at equivalent stocking rates (as percent reduction in peak biomass) for Potamogeton pectinatus/Najas spp. and Ceratophyllum demersum. The line represents equal control in the two macrophyte assemblages.

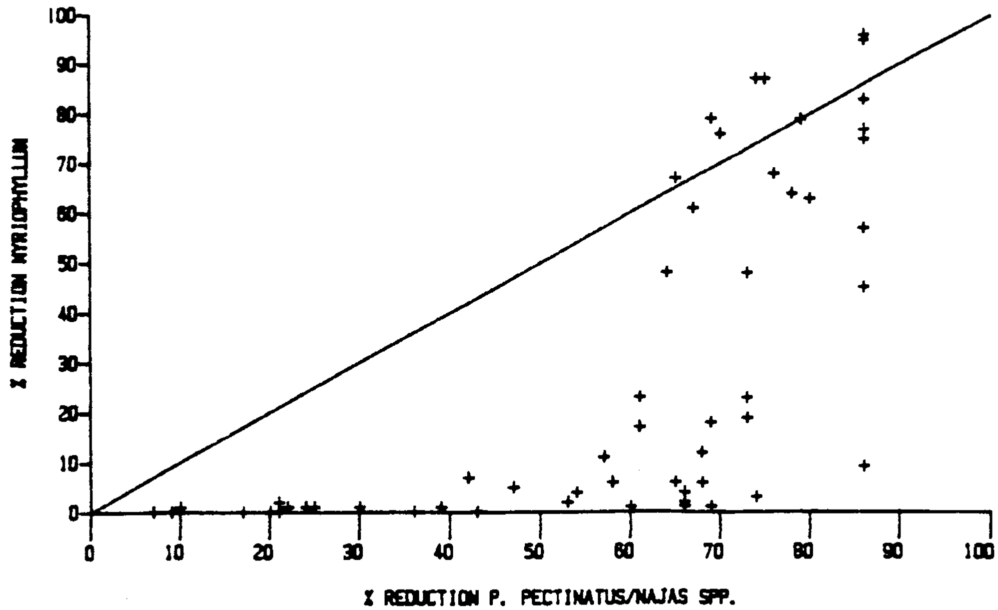


Fig. 2-9. Control at equivalent stocking rates (as percent reduction in peak biomass) for Potamogeton pectinatus/Najas spp. and Myriophyllum spp. The line represents equal control in the two macrophyte assemblages.

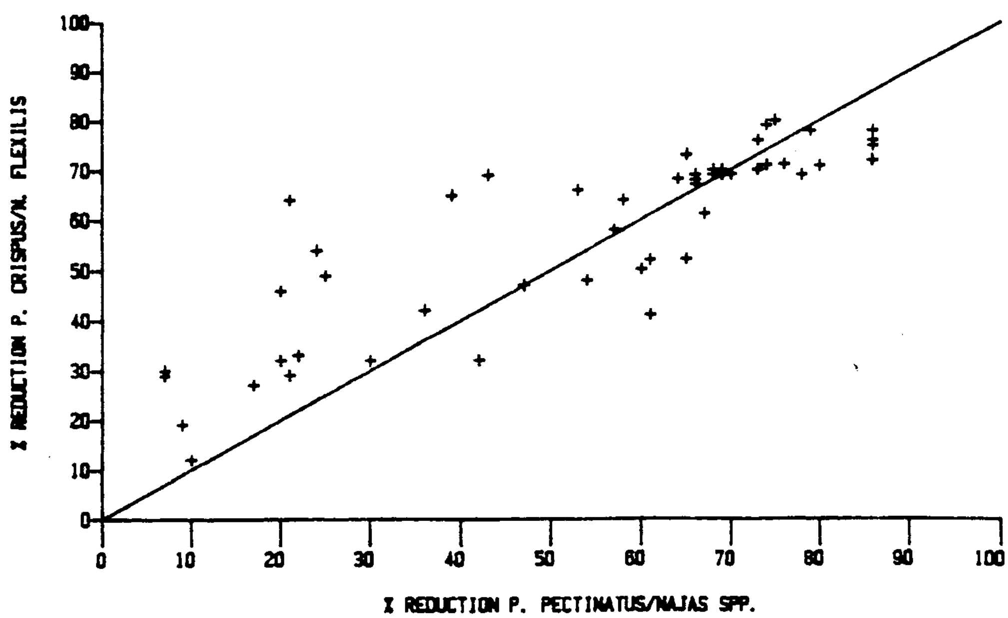


Fig. 2-12. Control at equivalent stocking rates (as percent reduction in peak biomass) for Potamogeton pectinatus/Najas spp. and Potamogeton crispus/Najas flexilis. The line represents equal control in the two macrophyte assemblages.

IHF3S SIMULATIONS USING A SERIAL STOCKING STRATEGY IN REGION 11

Simulated levels (g dry weight m^{-2}) of all five macrophyte assemblages are presented for both the best management practice (BMP) and eradication scenarios.

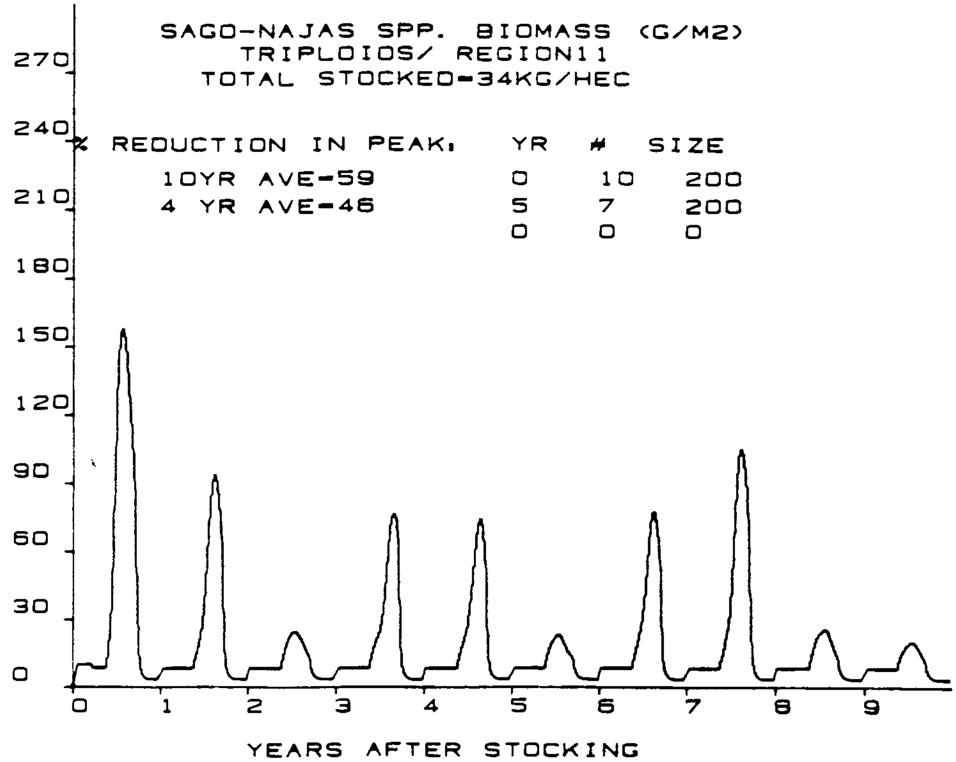


Fig. 2-1. BMP control of Potamogeton pectinatus/Najas spp. in Region 11.

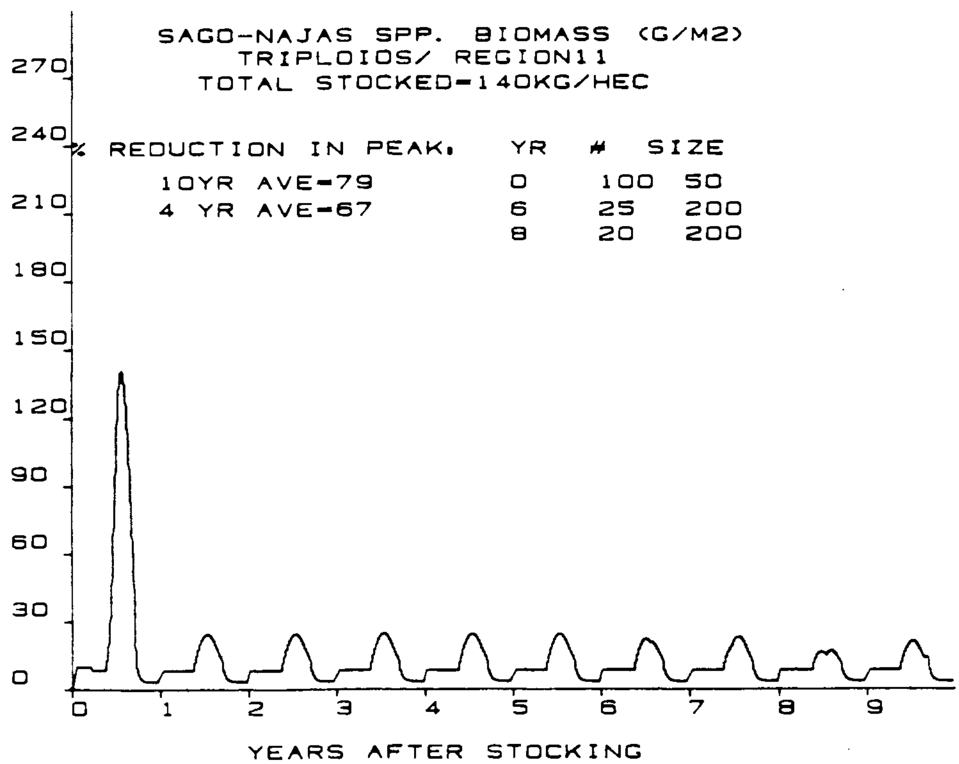


Fig. 2-2. Eradication of Potamogeton pectinatus/Najas spp. in Region 11.

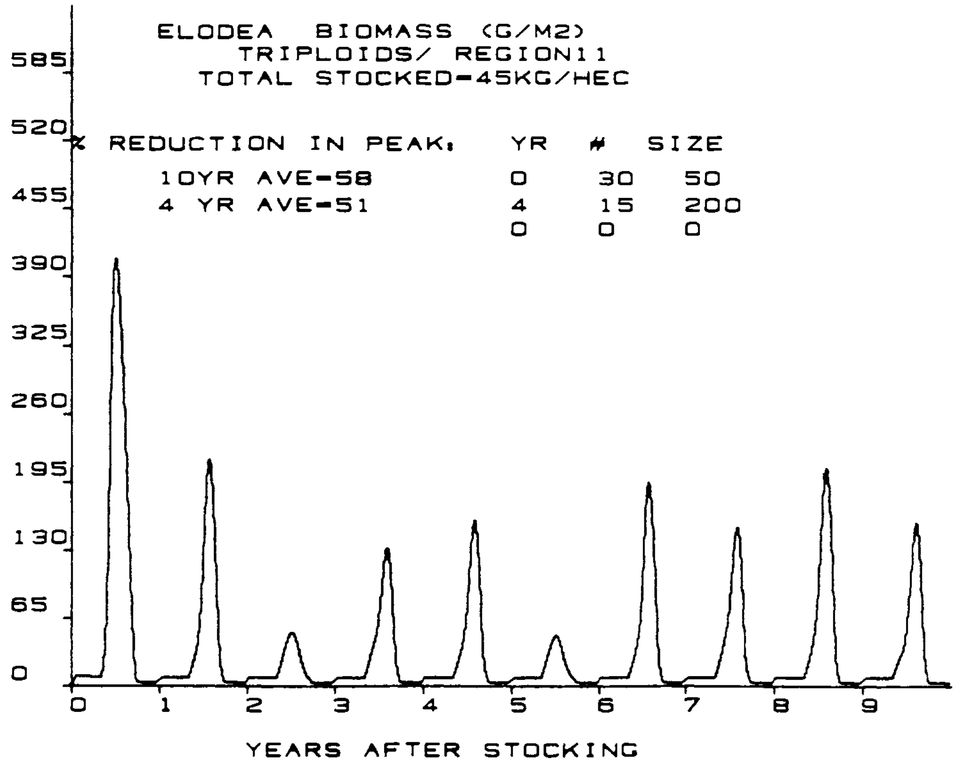


Fig. 2-4. BMP control of Elodea canadensis in Region 11.

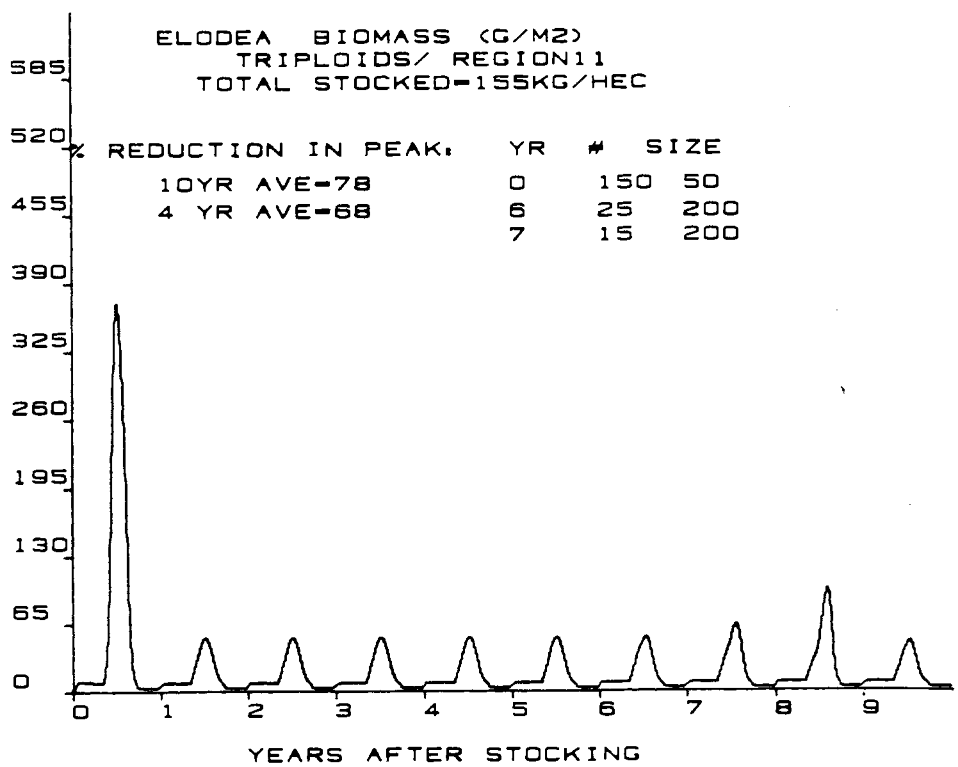


Fig. 2-5. Eradication of Elodea canadensis in Region 11.

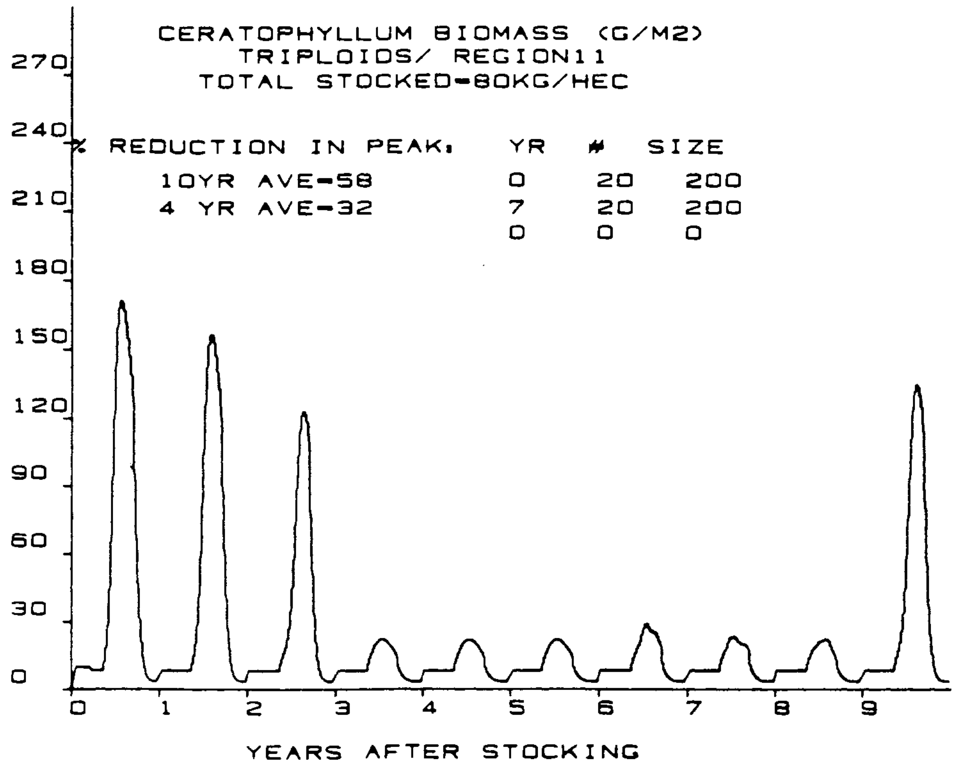


Fig. 2-7. BMP control of *Ceratophyllum demersum* in Region 11.

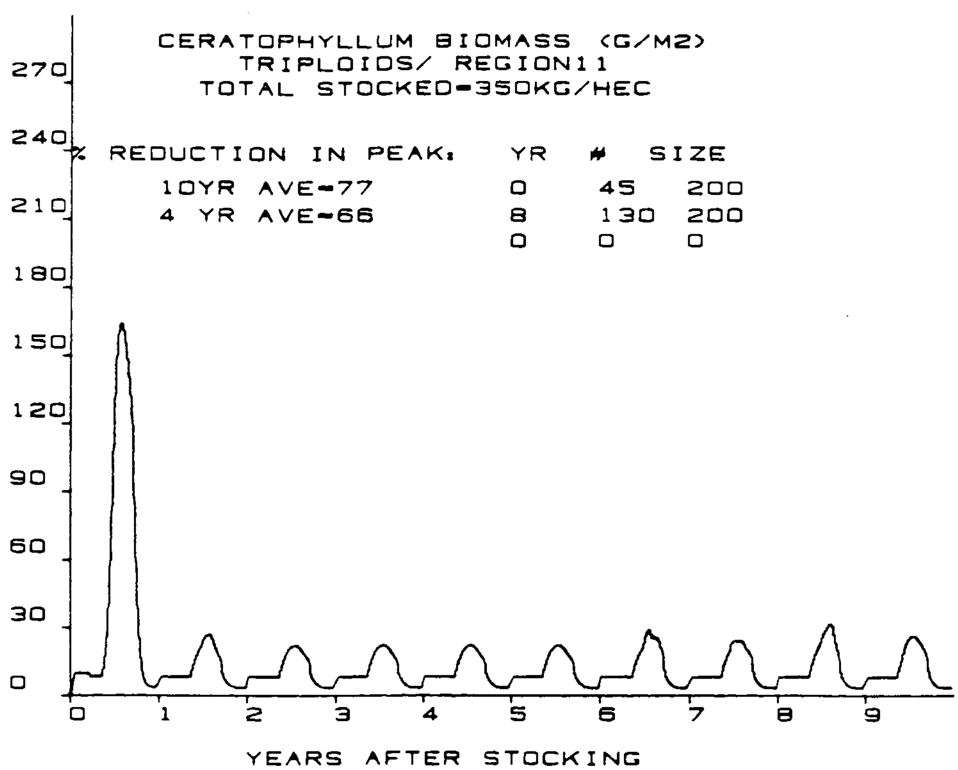


Fig. 2-8. Eradication of *Ceratophyllum demersum* in Region 11.

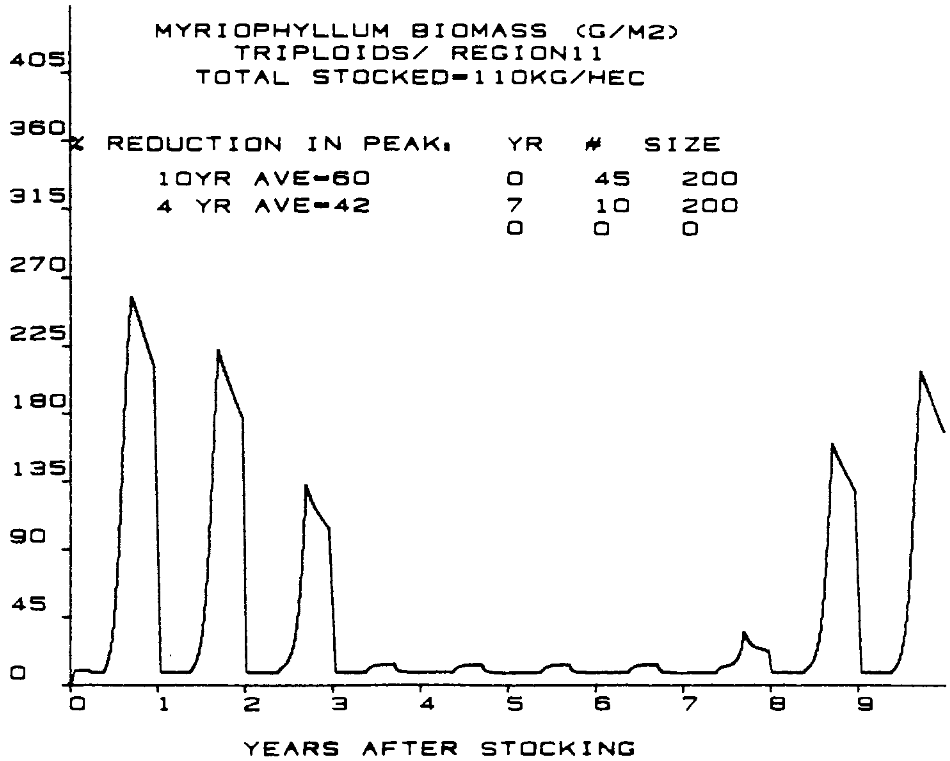


Fig. 2-10. BMP control of *Myriophyllum* spp. in Region 11.

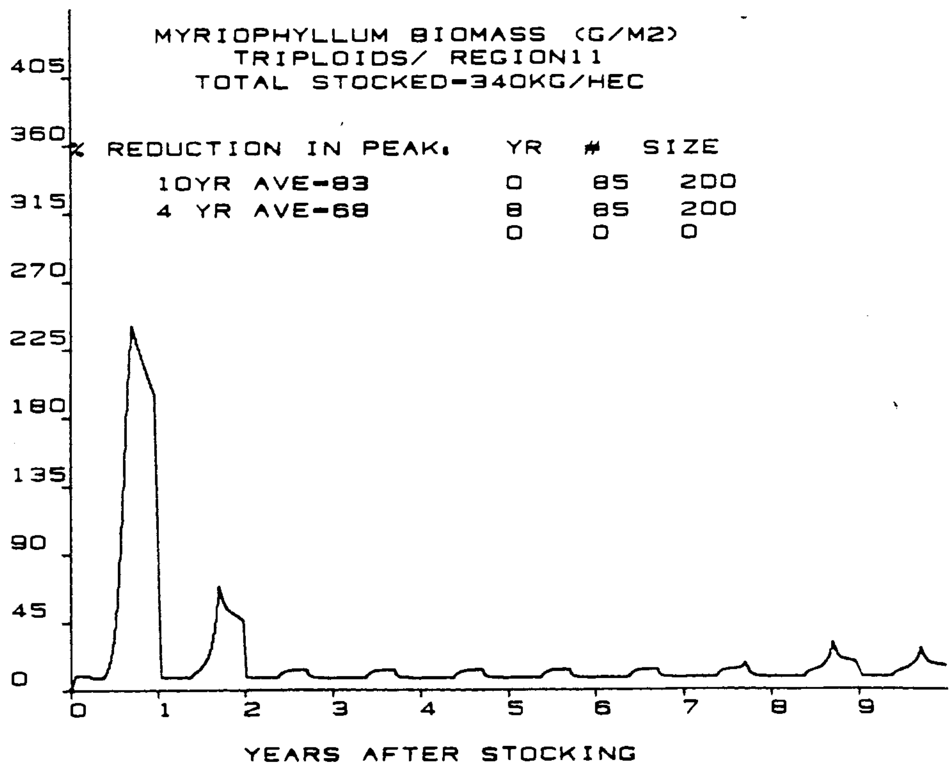


Fig. 2-11. Eradication of *Myriophyllum* spp. in Region 11.

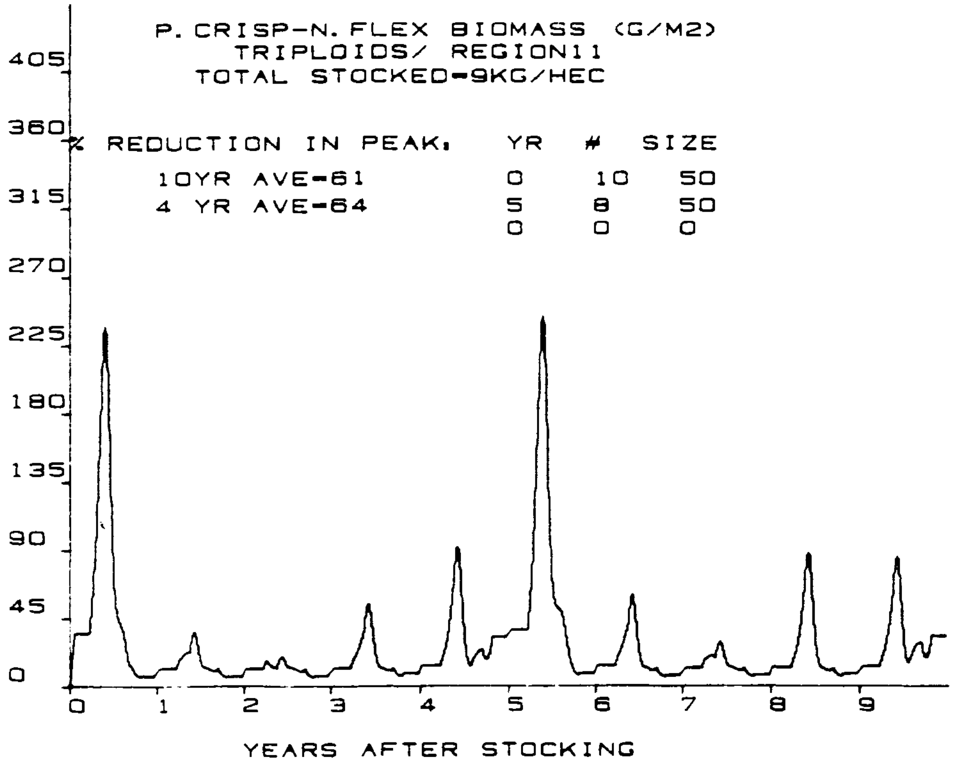


Fig. 2-13. BMP control of Potamogeton crispus/Najas flexilis in Region 11.

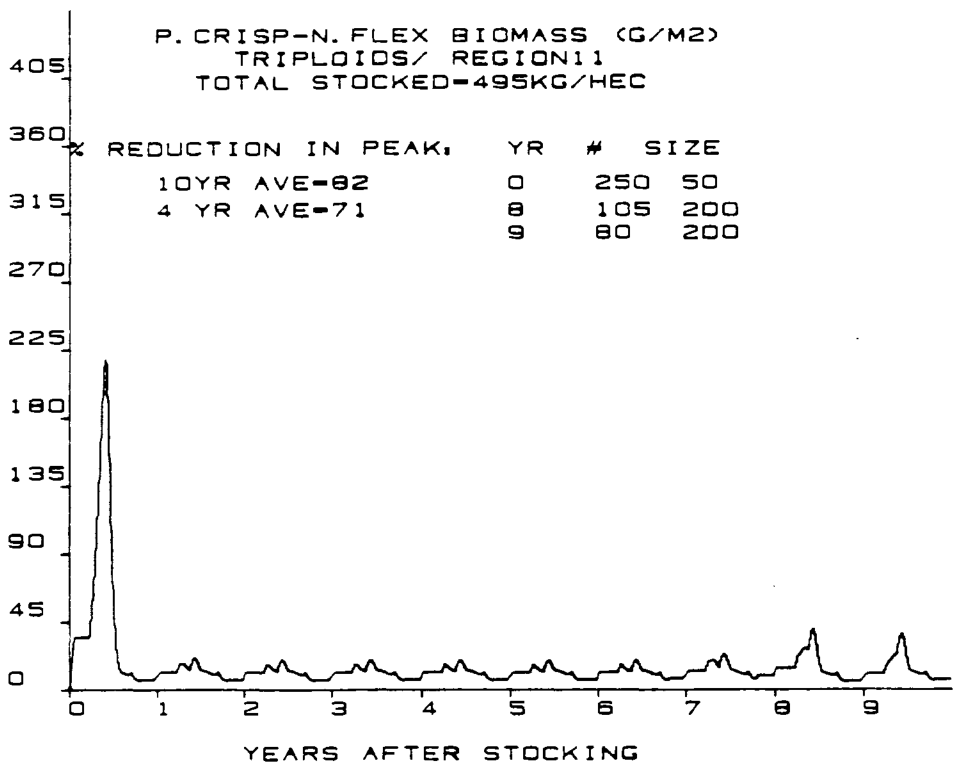


Fig. 2-14. Eradication of Potamogeton crispus/Najas flexilis in Region 11.

IHF3S SIMULATIONS USING A SERIAL STOCKING STRATEGY IN REGIONS 1, 6, 15, AND 19

Simulated levels (g dry weight m^{-2}) of all five macrophyte assemblages are presented for both the best management practice (BMP) and eradication scenarios.

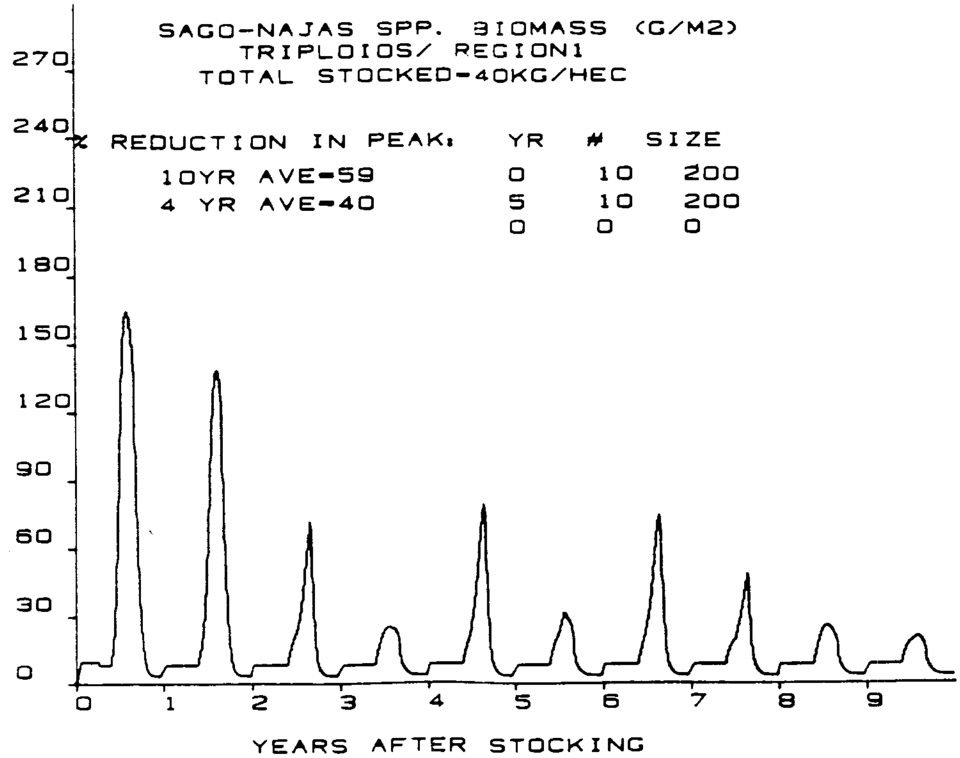


Fig. 2-15. BMP control of Potamogeton pectinatus/Najas spp. in Region 1.

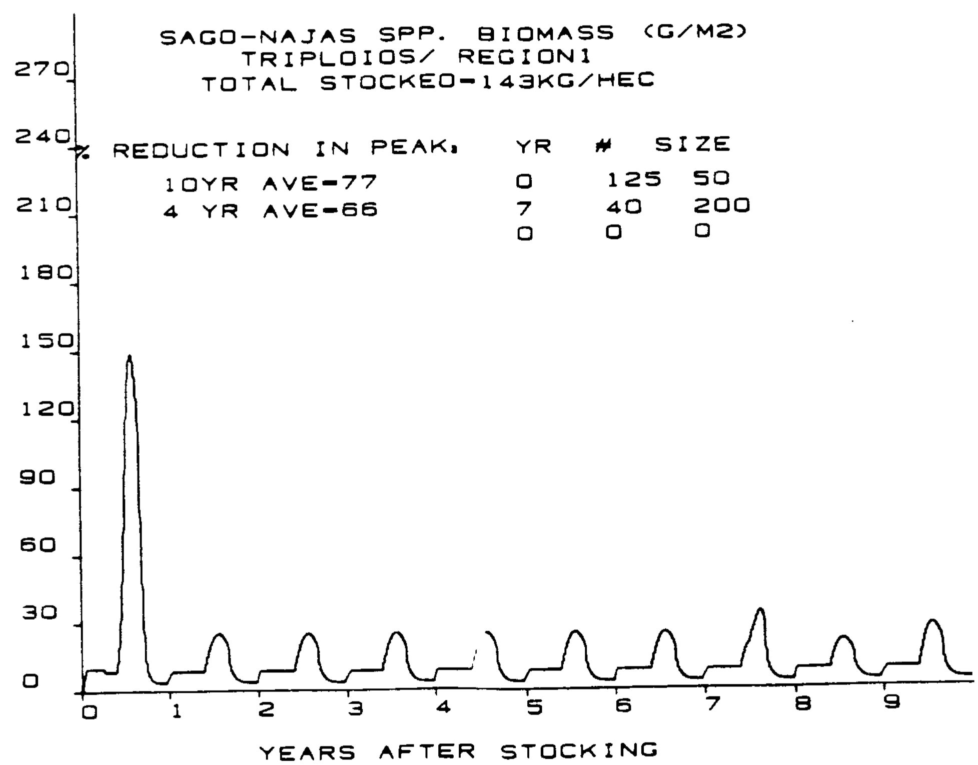


Fig. 2-16. Eradication of Potamogeton pectinatus/Najas spp. in Region 1.

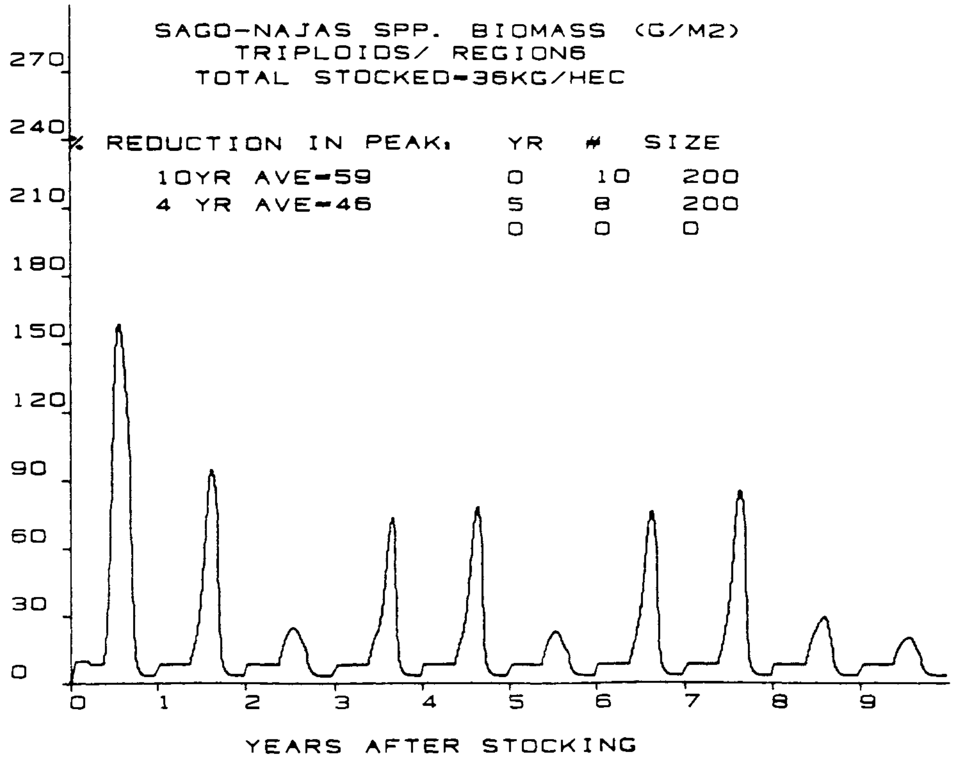


Fig. 2-17. BMP control of Potamogeton pectinatus/Najas spp. in Region 6.

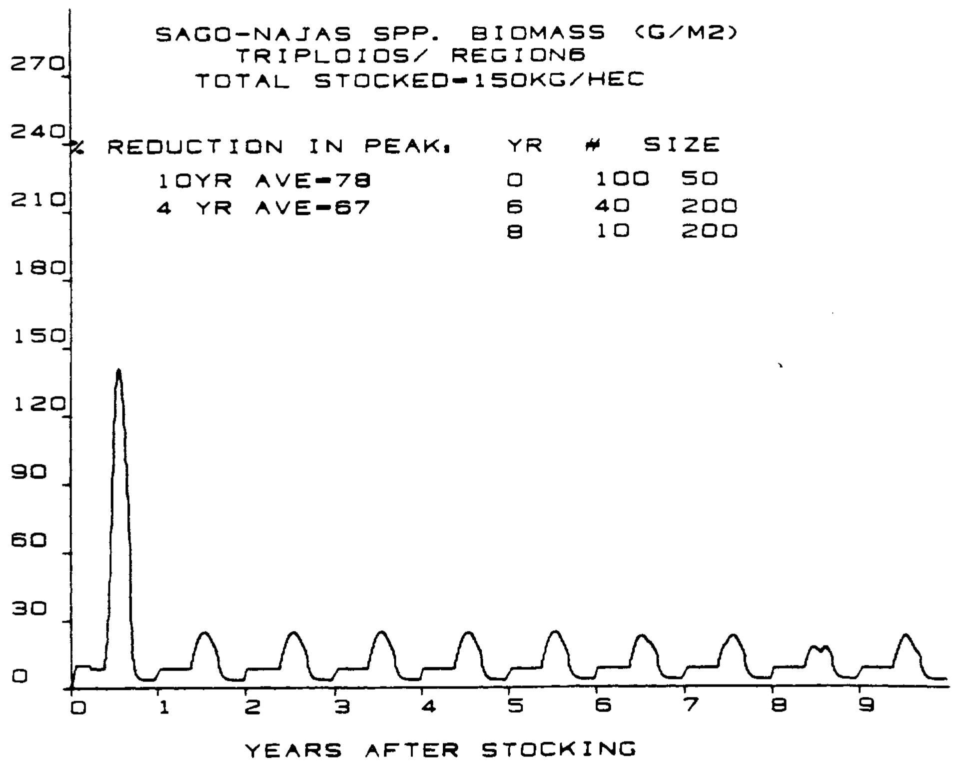


Fig. 2-18. Eradication of Potamogeton pectinatus/Najas spp. in Region 6.

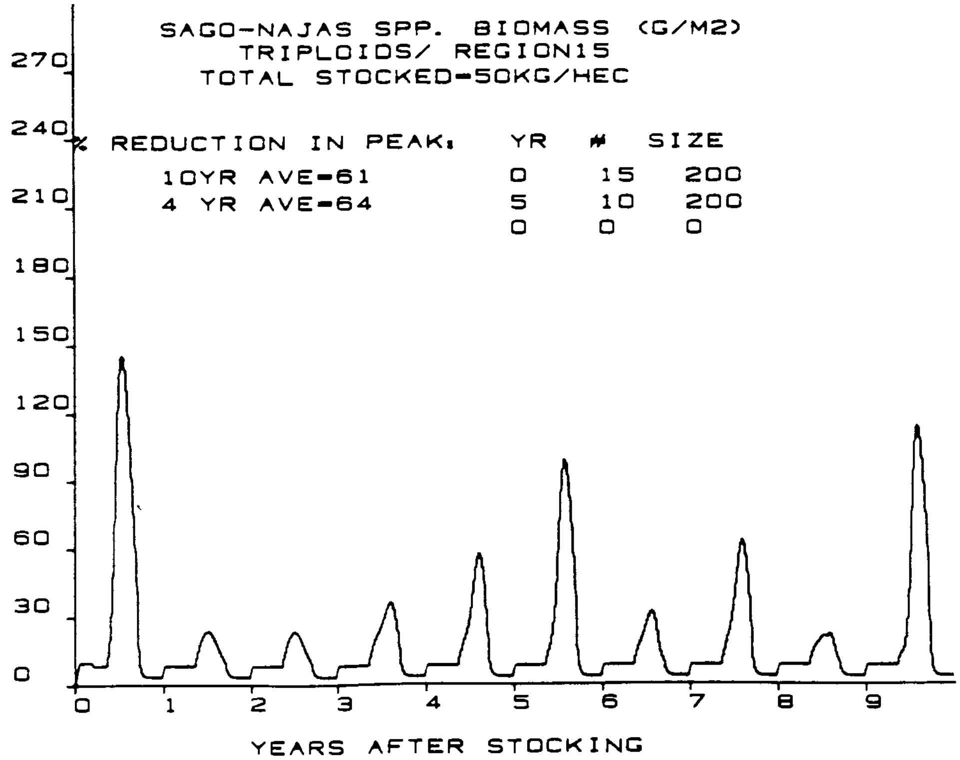


Fig. 2-19. BMP control of Potamogeton pectinatus/Najas spp. in Region 15.

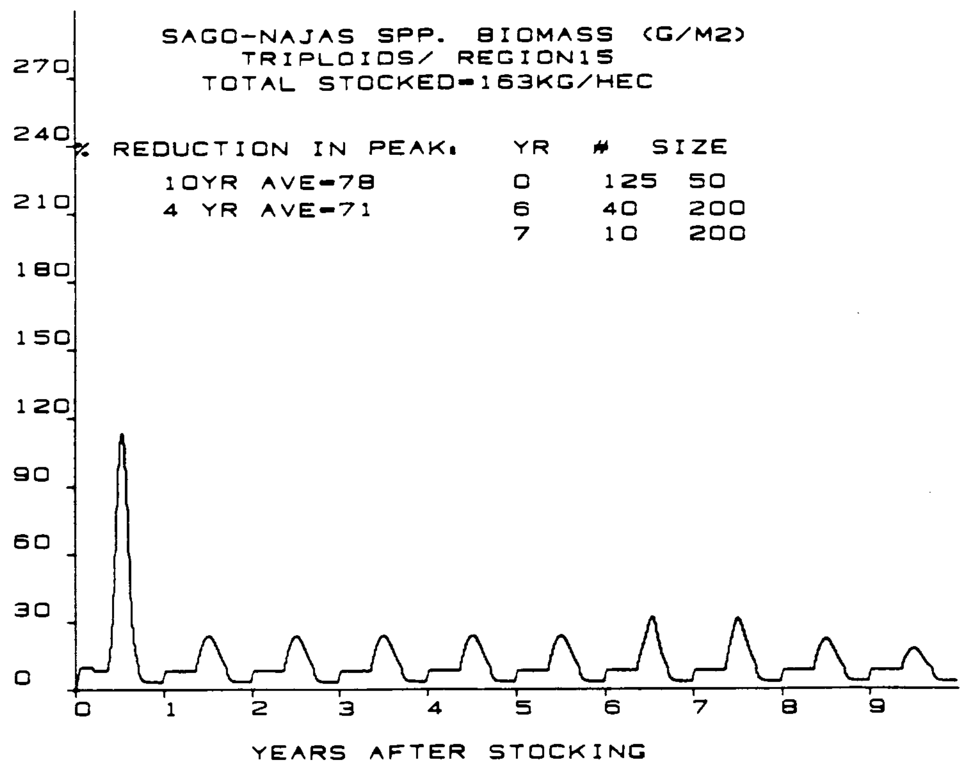


Fig. 2-20. Eradication of Potamogeton pectinatus/Najas spp. in Region 15.

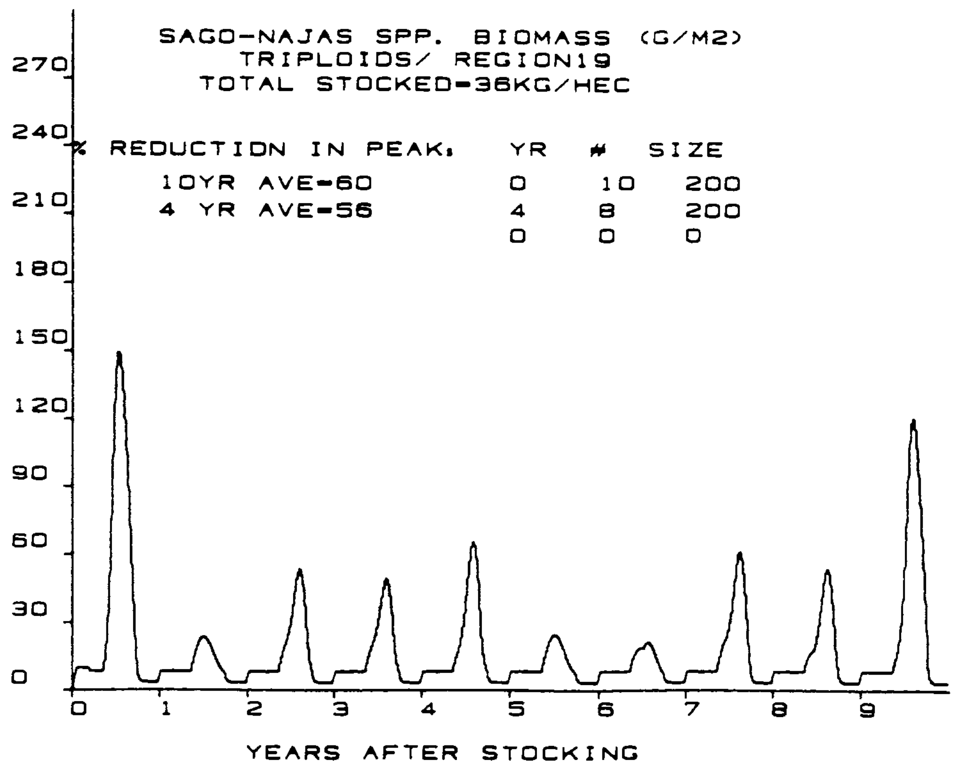


Fig. 2-21. BMP control of Potamogeton pectinatus/Najas spp. in Region 19.

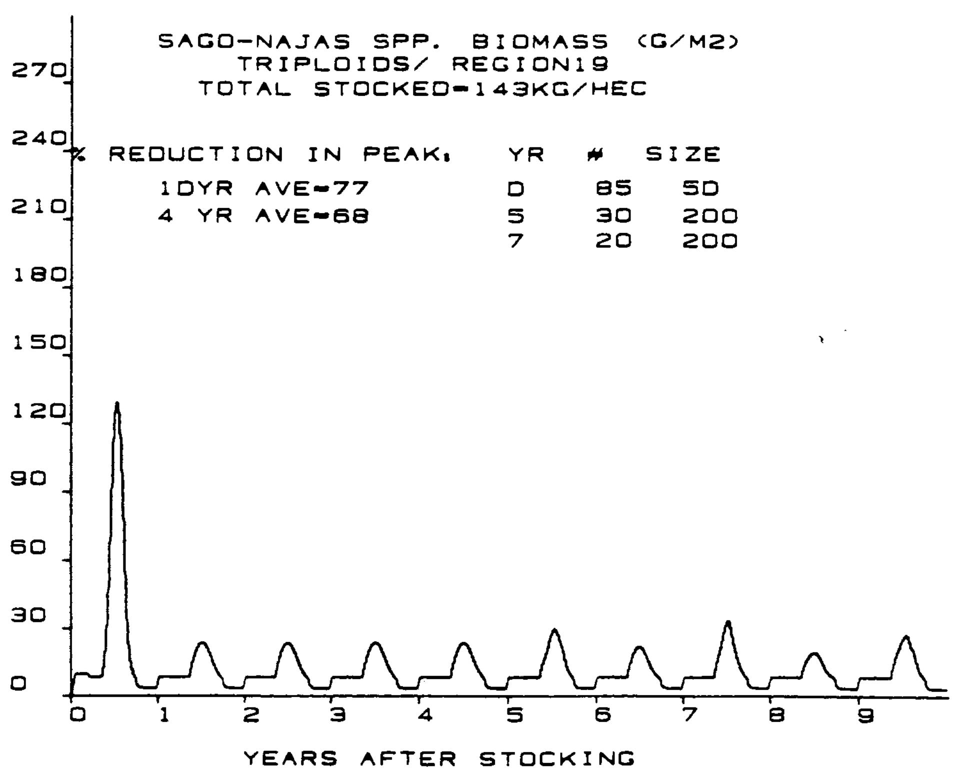


Fig. 2-22. Eradication of Potamogeton pectinatus/Najas spp. in Region 19.

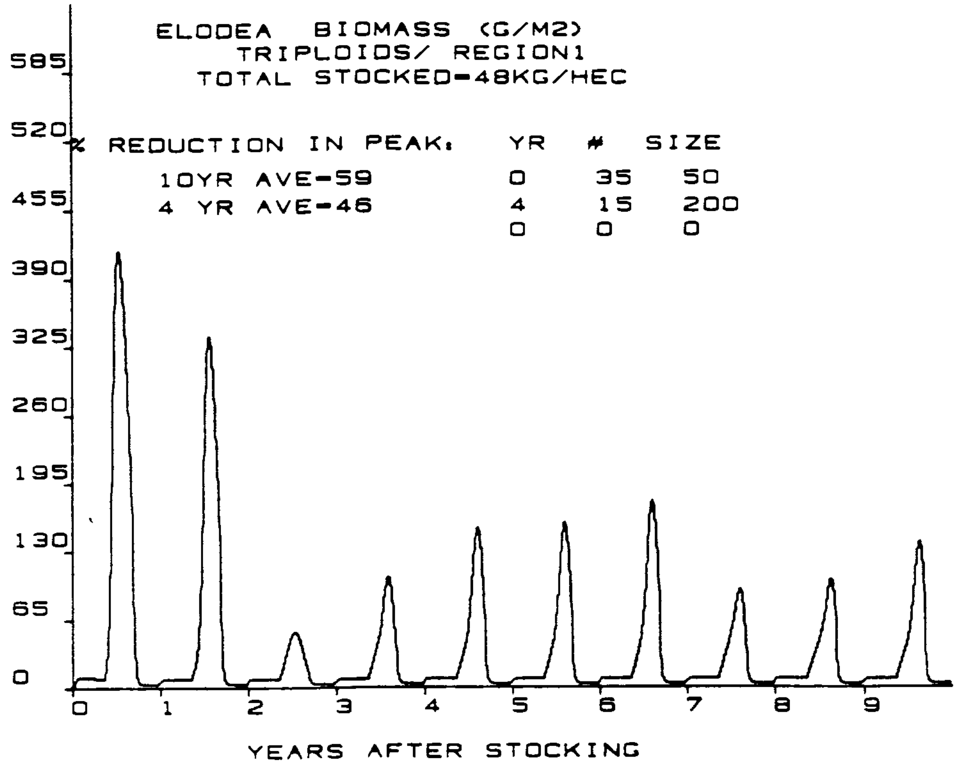


Fig. 2-23. BMP control of _Elodea canadensis_ in Region 1.

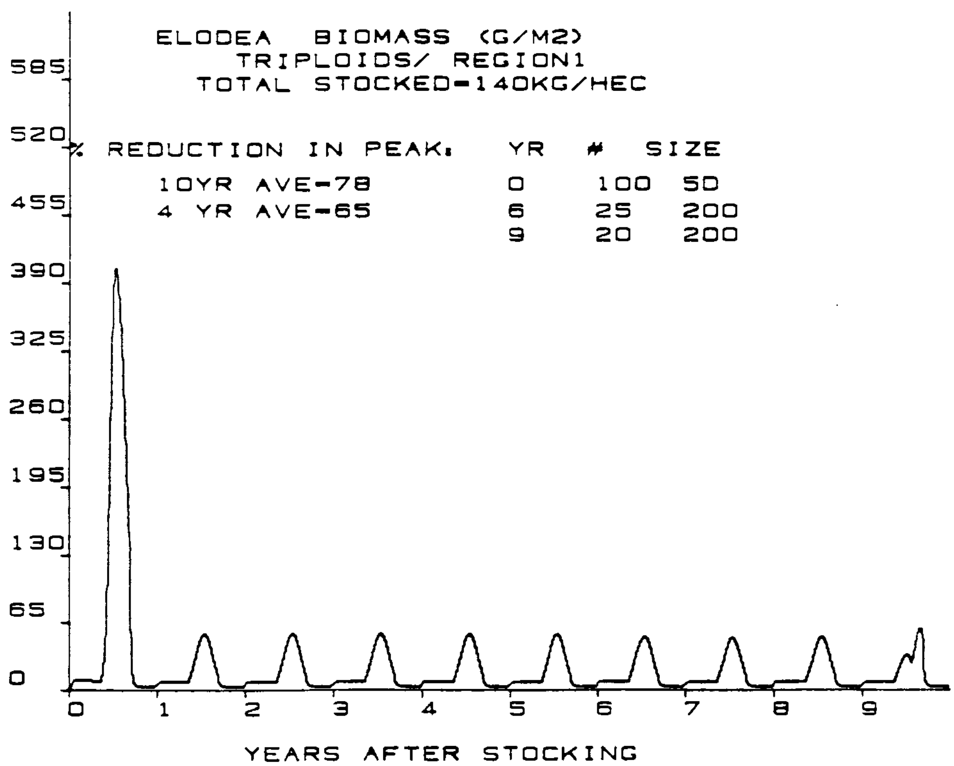


Fig. 2-24. Eradication of _Elodea canadensis_ in Region 1.

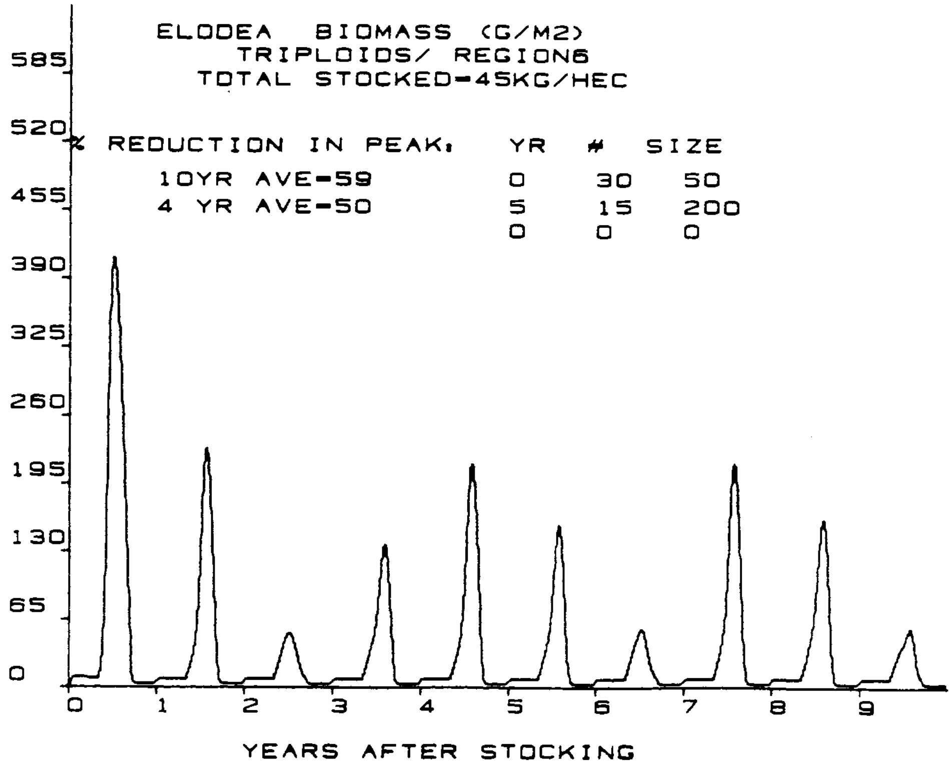


Fig. 2-25. BMP control of *Elodea canadensis* in Region 6.

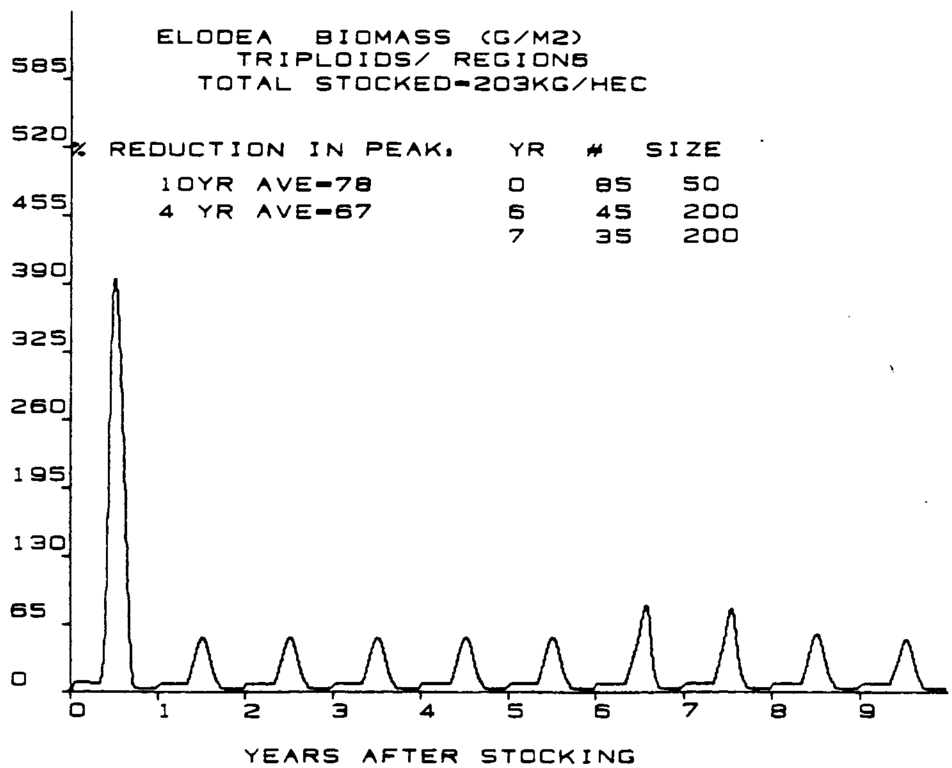


Fig. 2-26. Eradication of *Elodea canadensis* in Region 6.

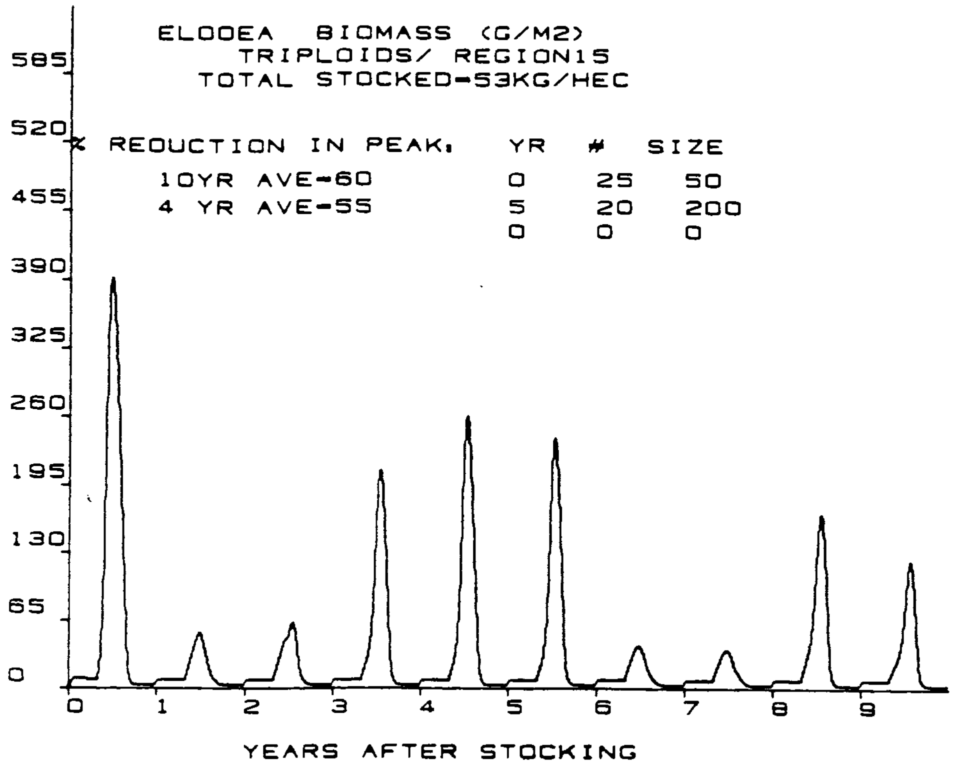


Fig. 2-27. BMP control of <u>Elodea canadensis</u> in Region 15.

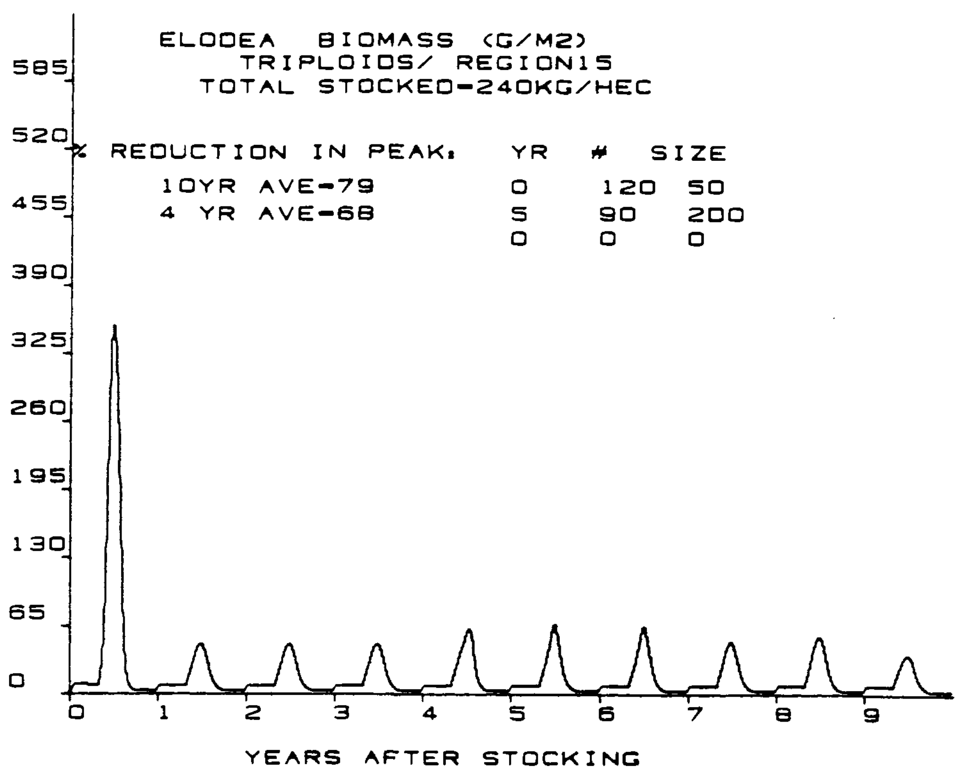


Fig. 2-28. Eradication of <u>Elodea canadensis</u> in Region 15.

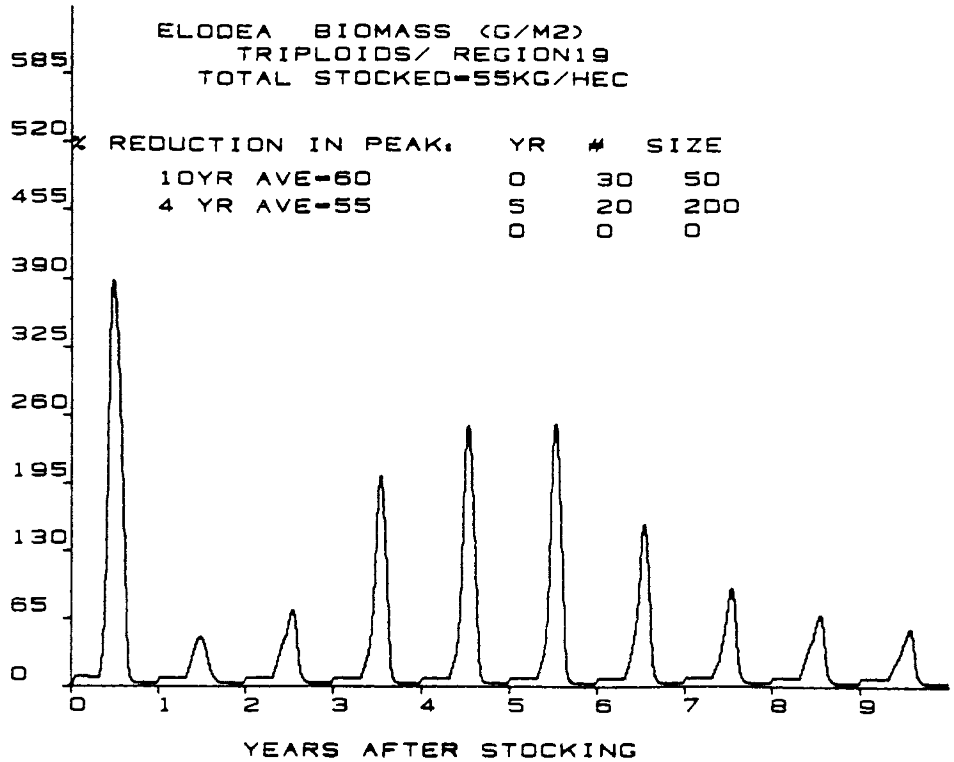


Fig. 2-29. BMP control of <u>Elodea canadensis</u> in Region 19.

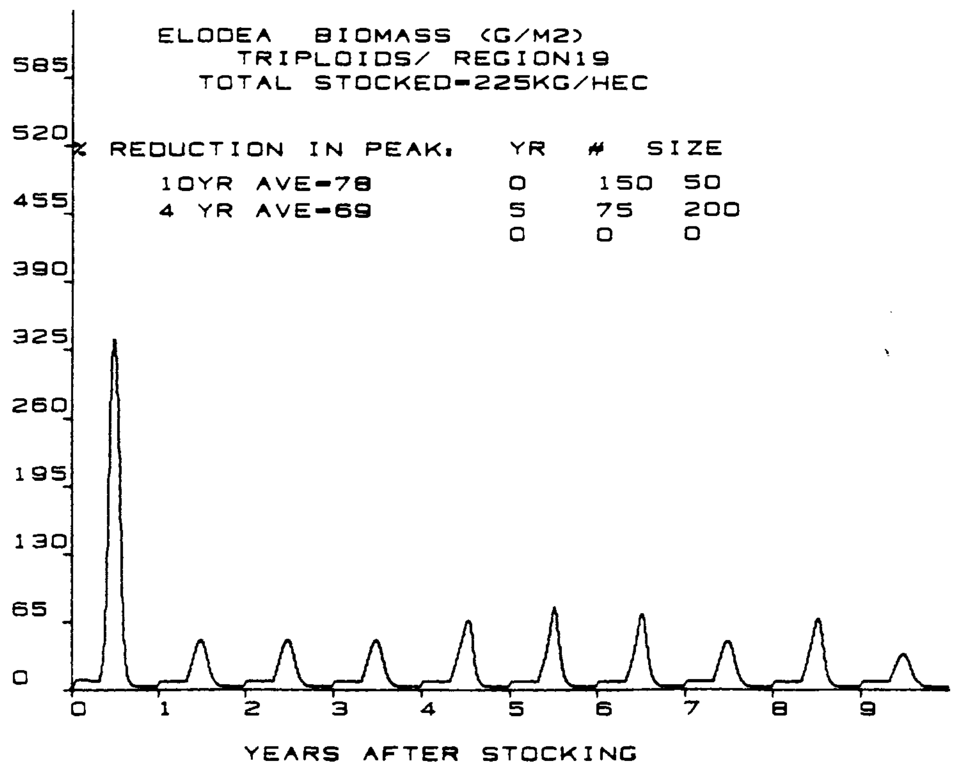


Fig. 2-30. Eradication of <u>Elodea canadensis</u> in Region 19.

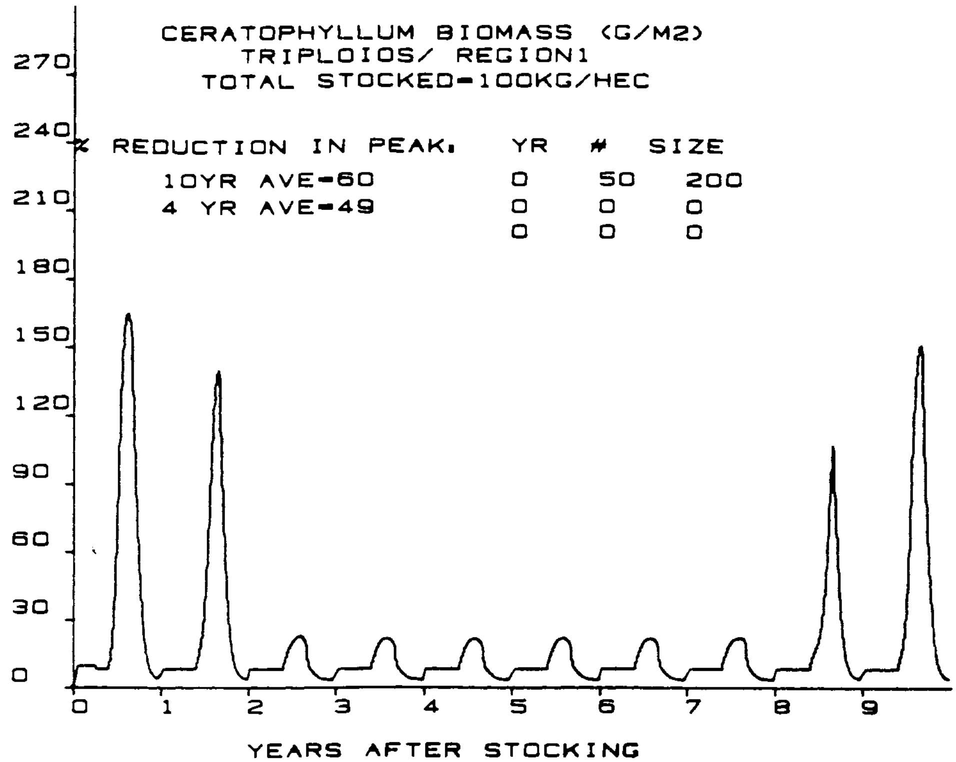


Fig. 2-31. BMP control of <u>Ceratophyllum demersum</u> in Region 1.

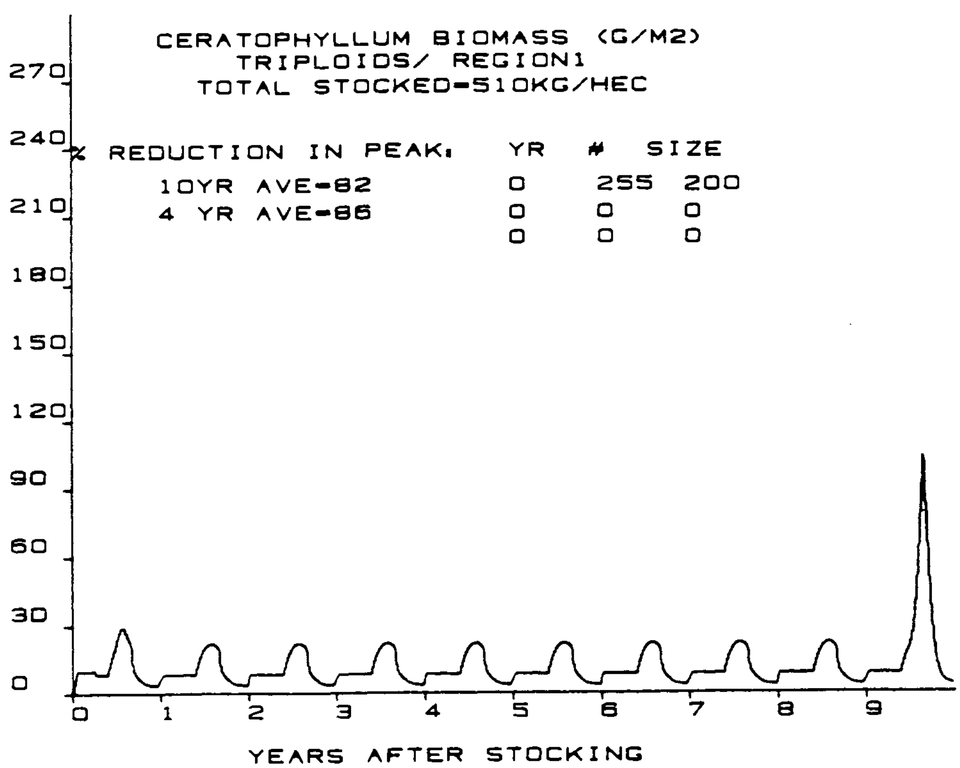


Fig. 2-32. Eradication of <u>Ceratophyllum demersum</u> in Region 1.

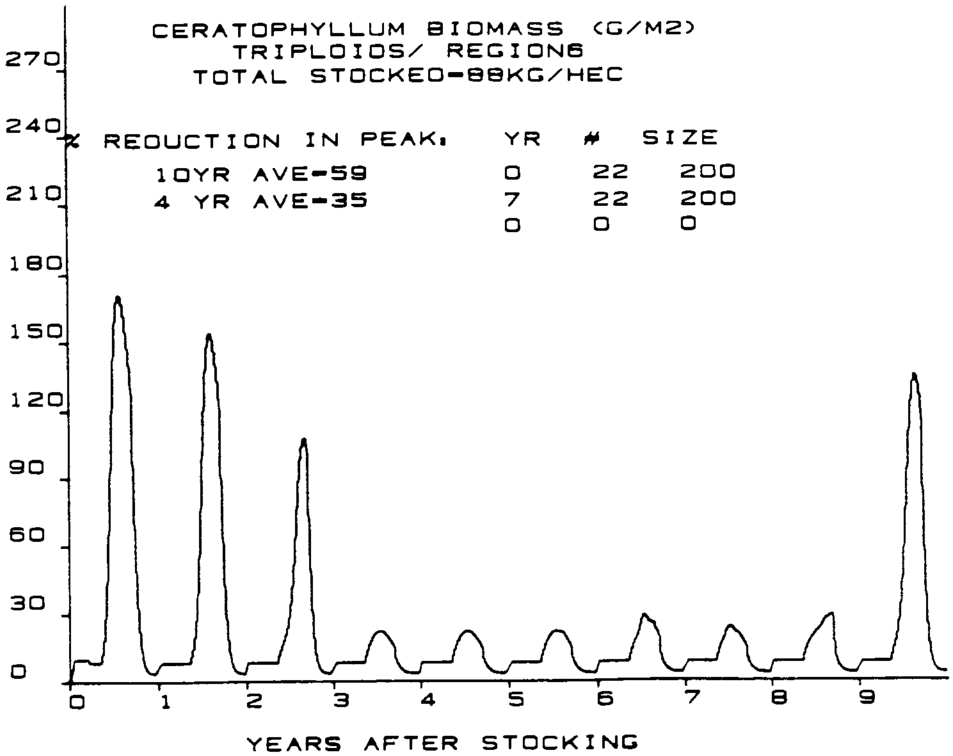


Fig. 2-33. BMP control of Ceratophyllum demersum in Region 6.

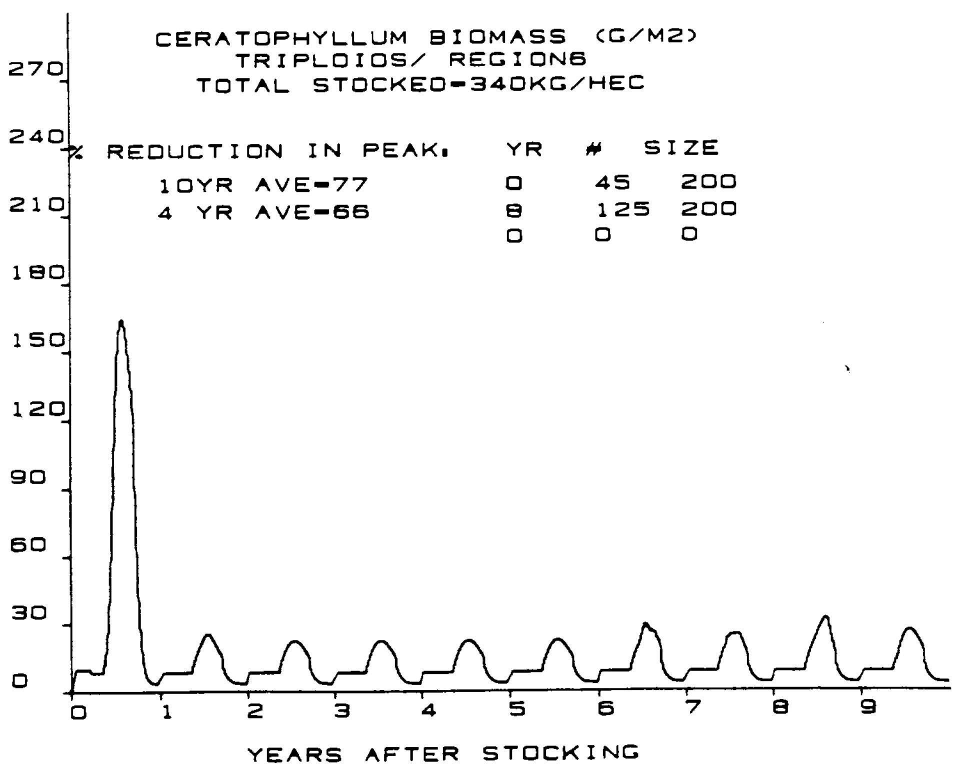


Fig. 2-34. Eradication of Ceratophyllum demersum in Region 6.

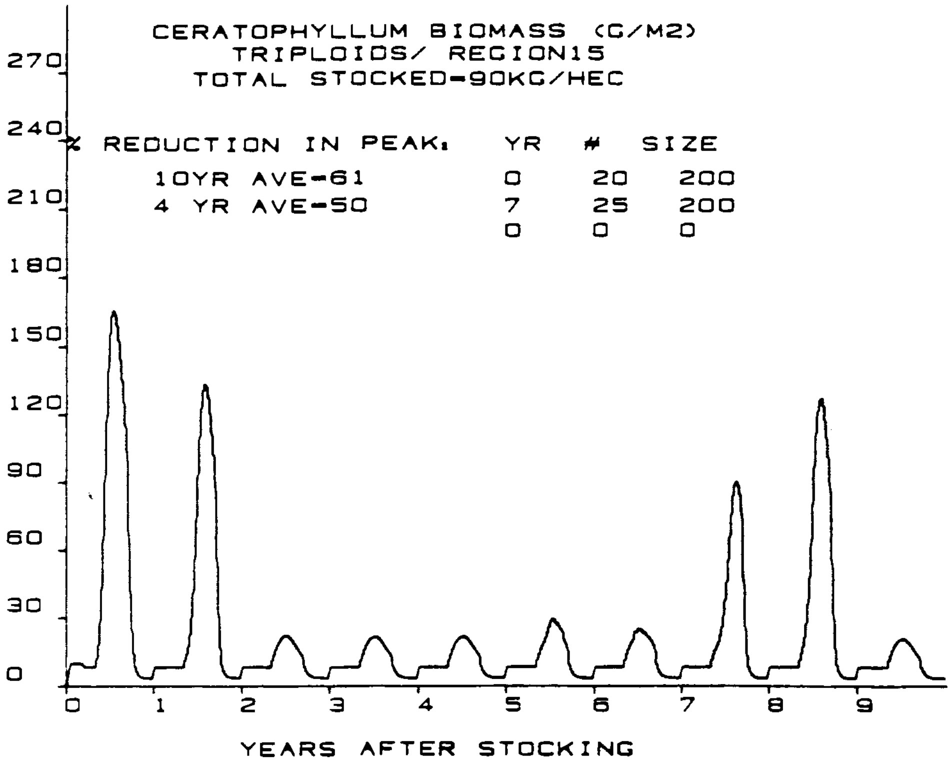


Fig. 2-35. BMP control of *Ceratophyllum demersum* in Region 15.

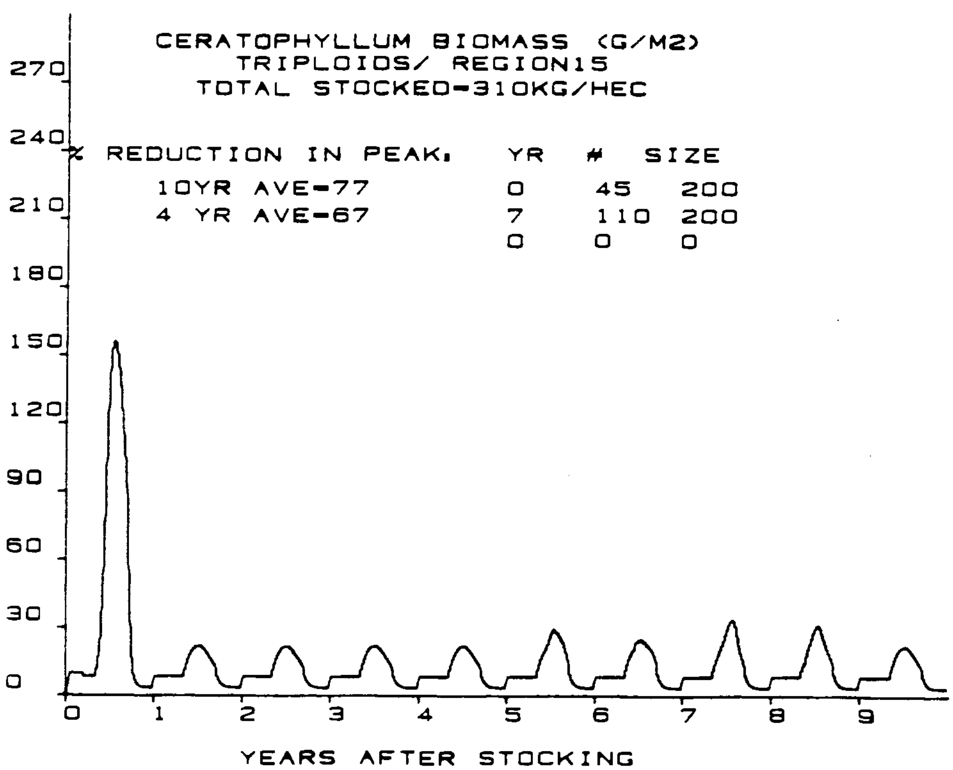


Fig. 2-36. Eradication of *Ceratophyllum demersum* in Region 15.

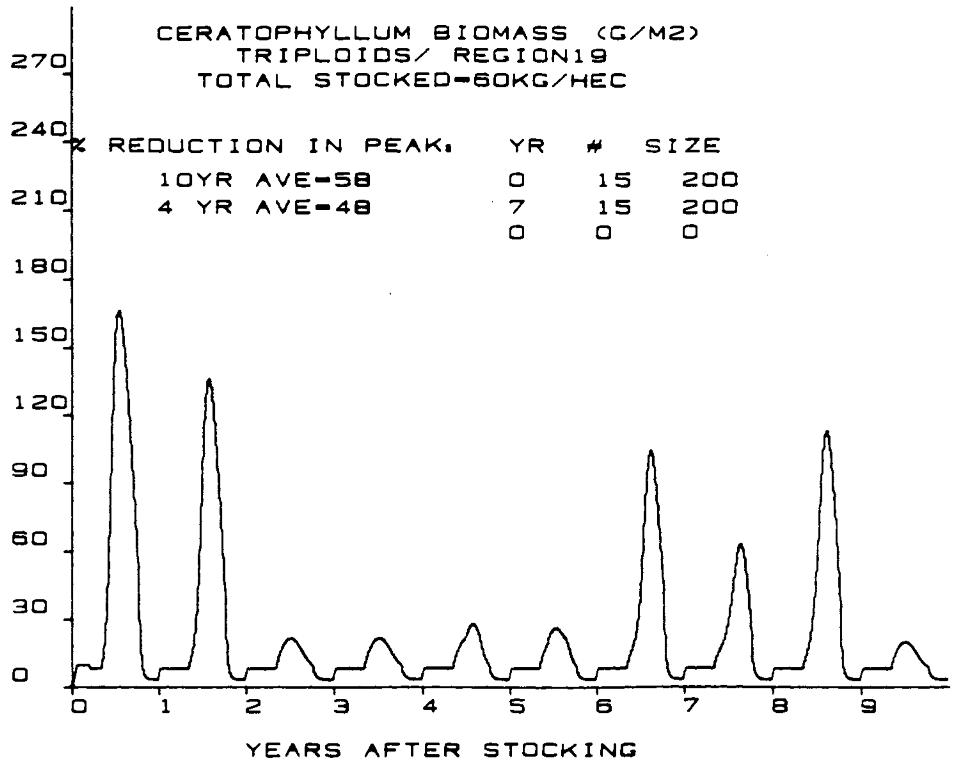


Fig. 2-37. BMP control of *Ceratophyllum demersum* in Region 19.

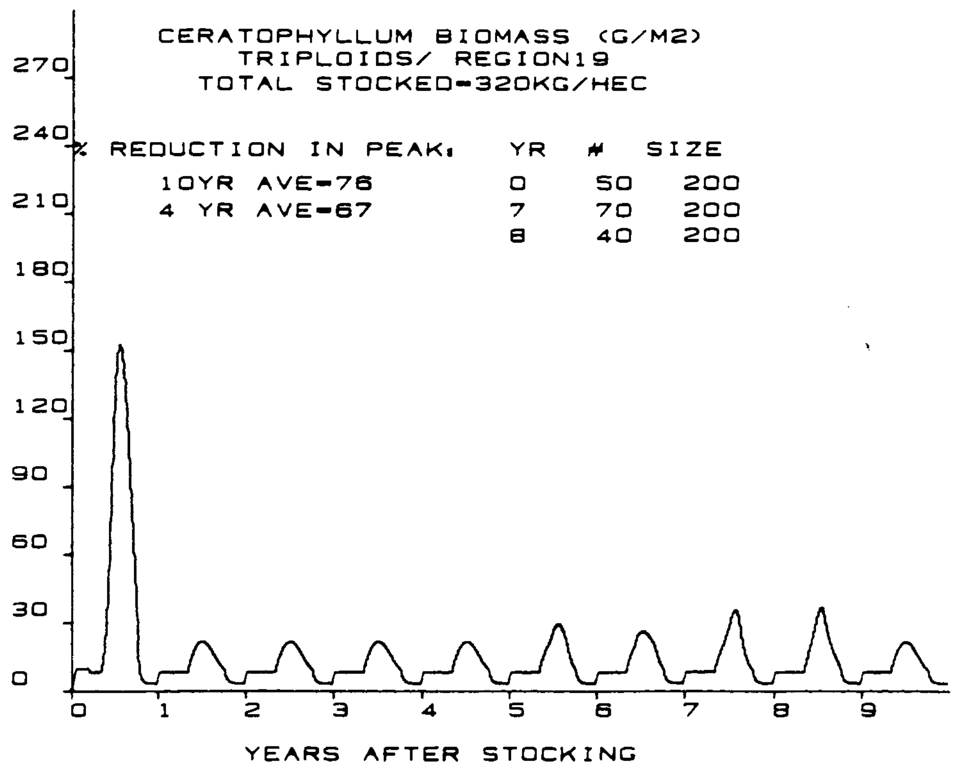


Fig. 2-38. Eradication of *Ceratophyllum demersum* in Region 19.

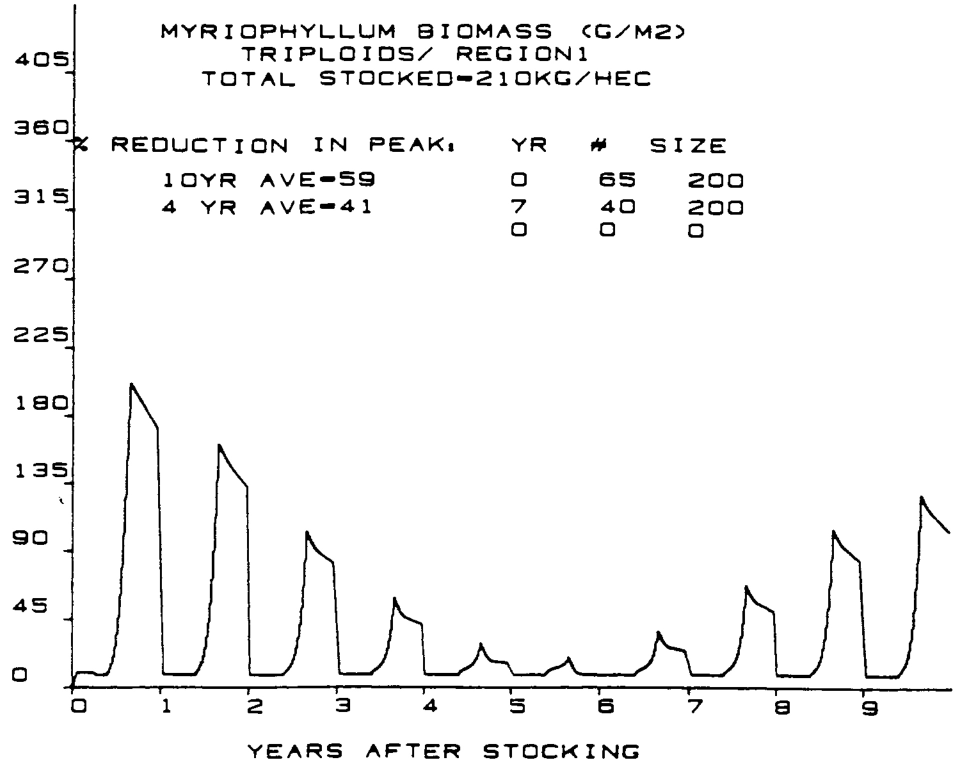


Fig. 2-39. BMP control of _Myriophyllum_ spp. in Region 1.

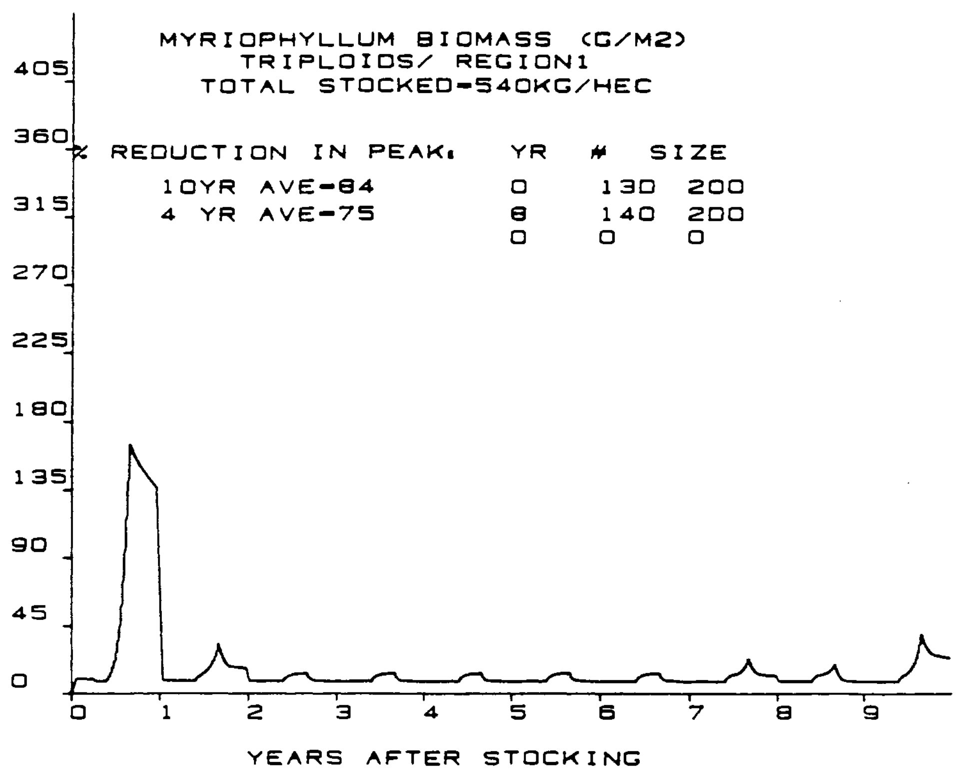


Fig. 2-40. Eradication of _Myriophyllum_ spp. in Region 1.

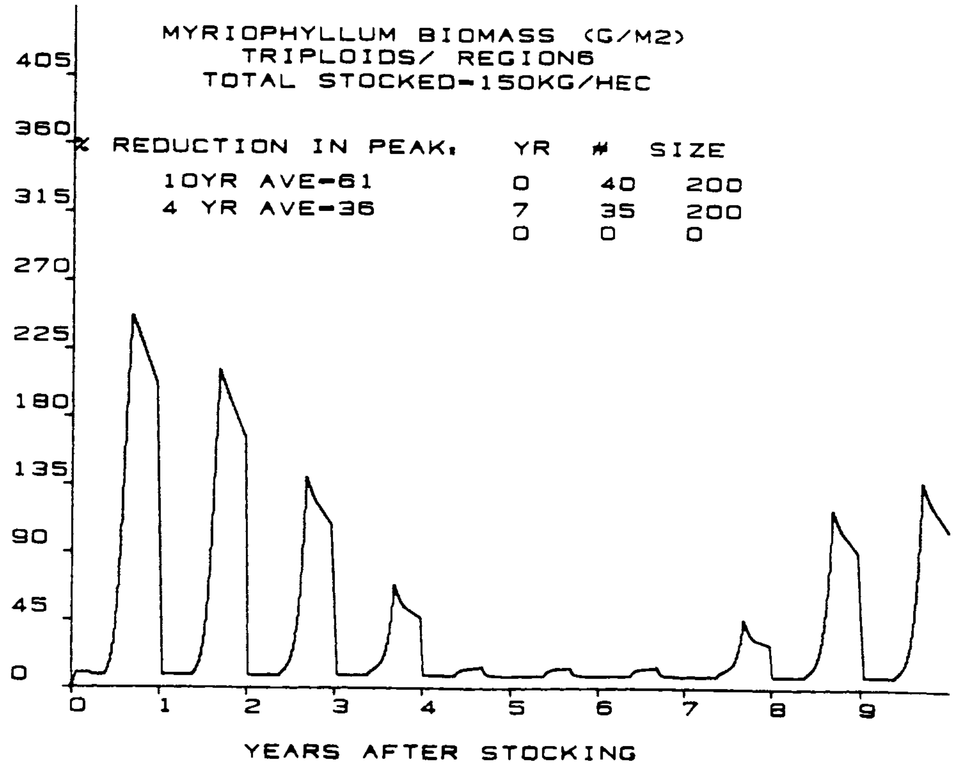


Fig. 2-41. BMP control of <u>Myriophyllum</u> spp. in Region 6.

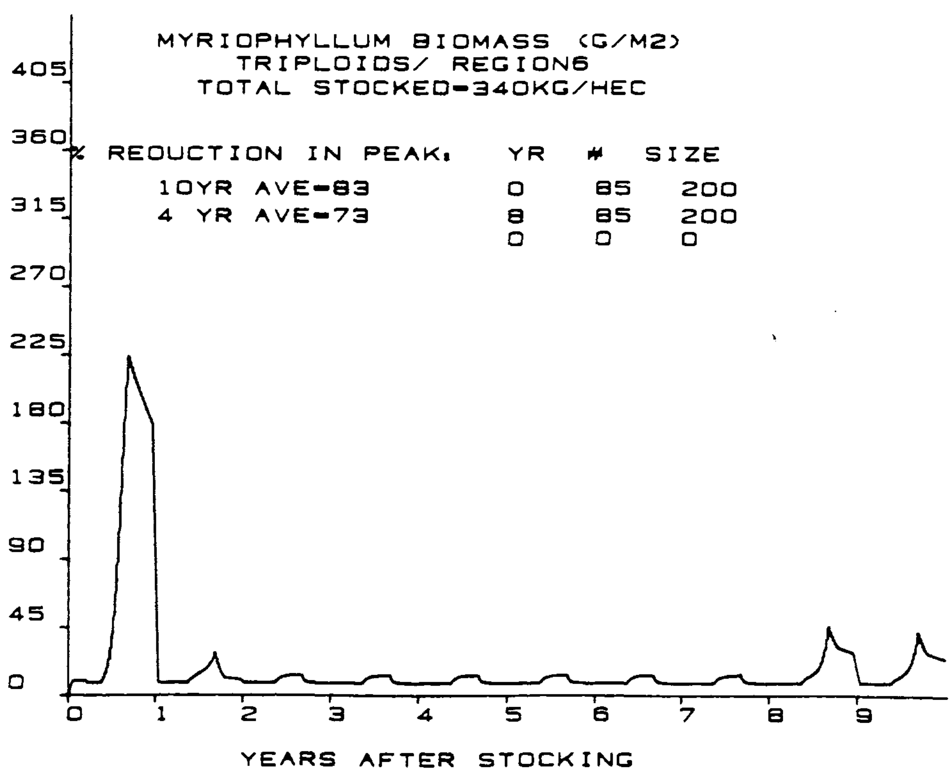


Fig. 2-42. Eradication of <u>Myriophyllum</u> spp. in Region 6.

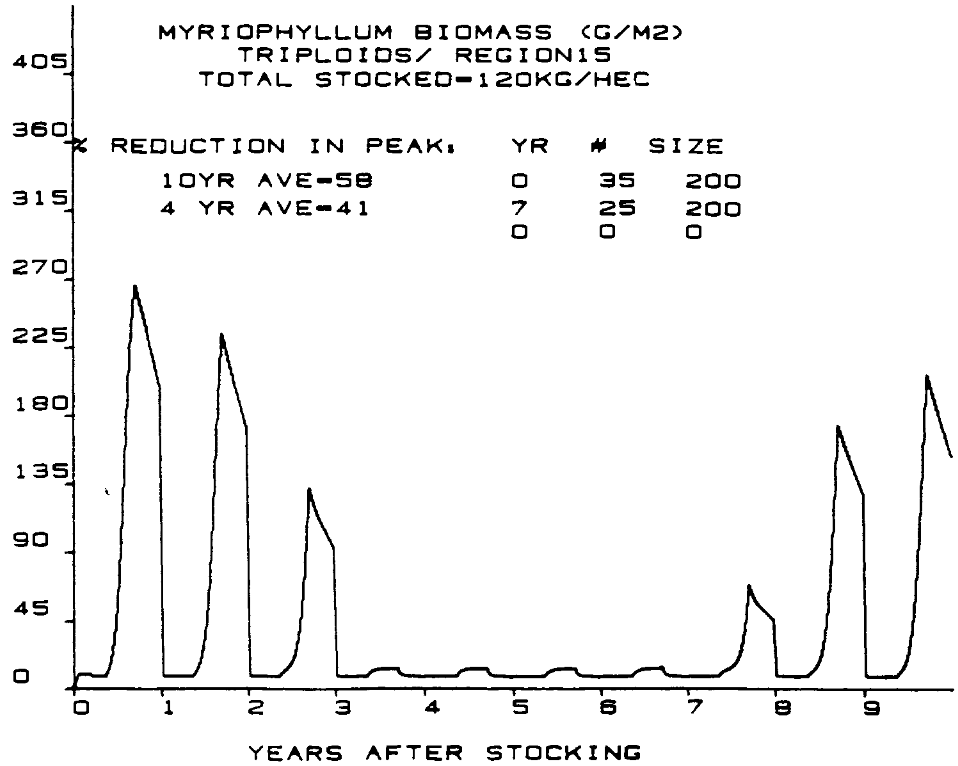


Fig. 2-43. BMP control of *Myriophyllum* spp. in Region 15.

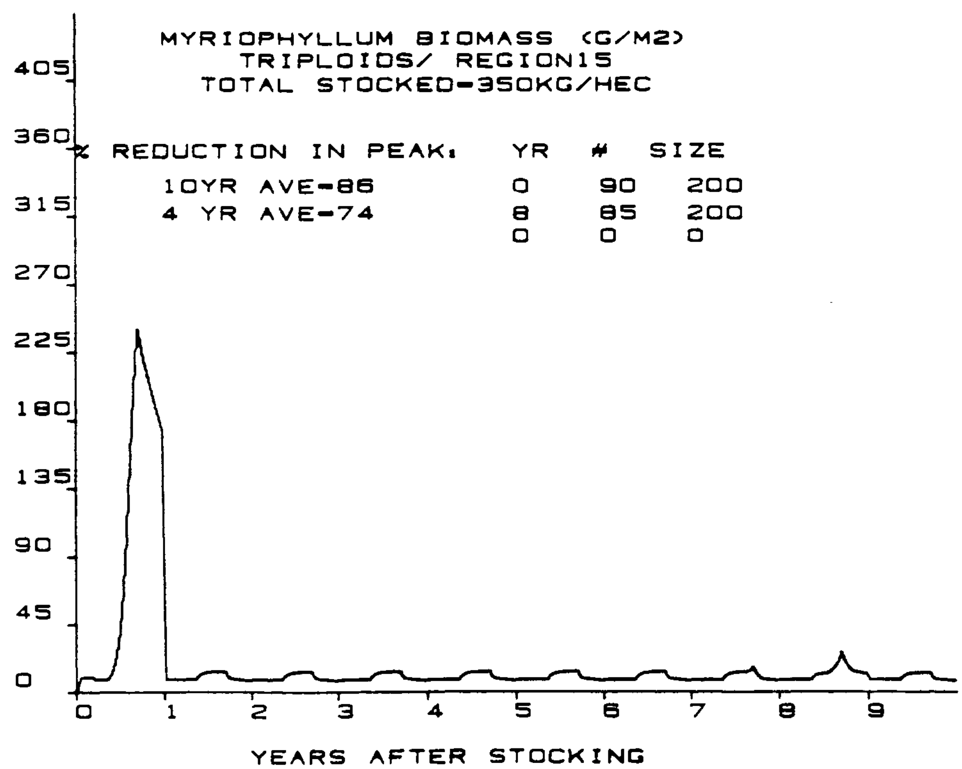


Fig. 2-44. Eradication of *Myriophyllum* spp. in Region 15.

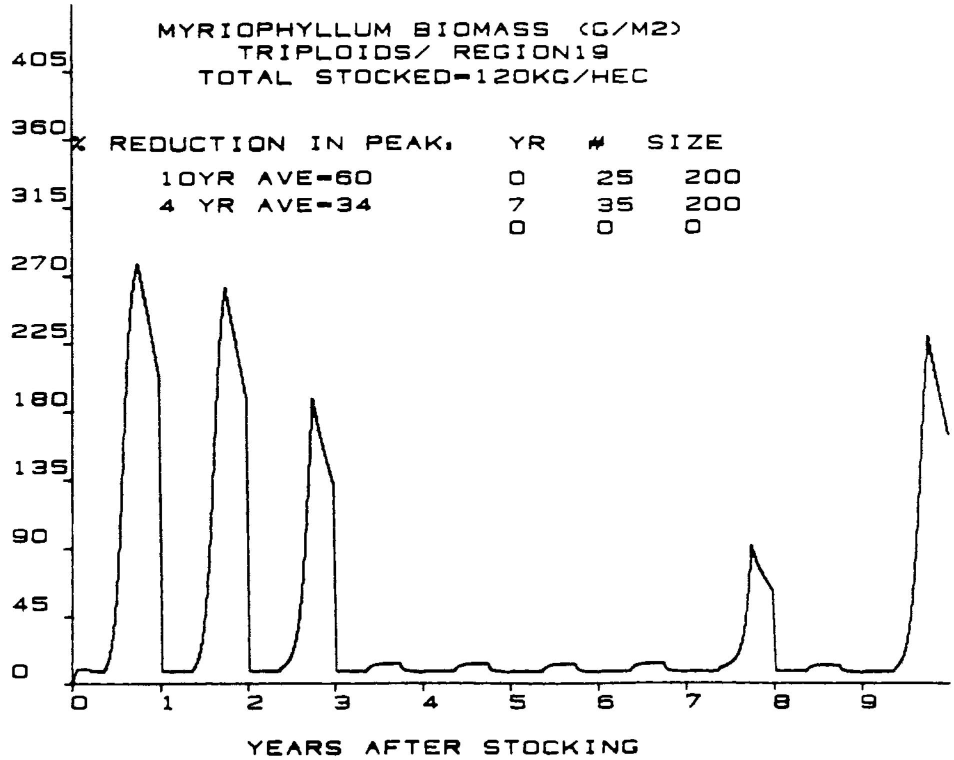


Fig. 2-45. BMP control of Myriophyllum spp. in Region 19.

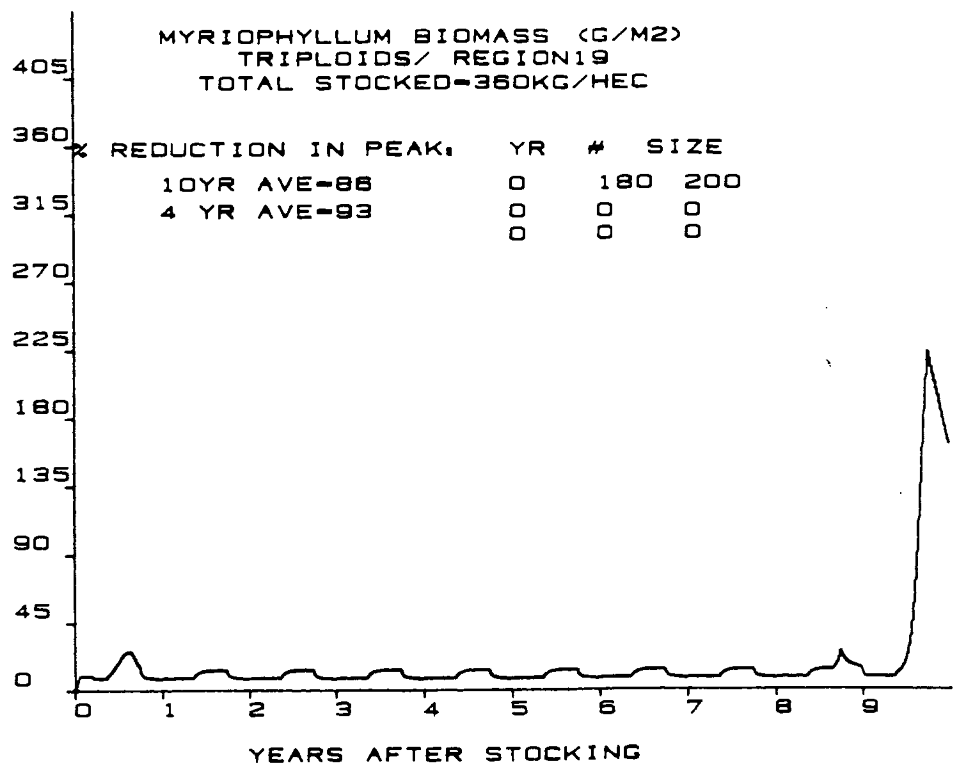
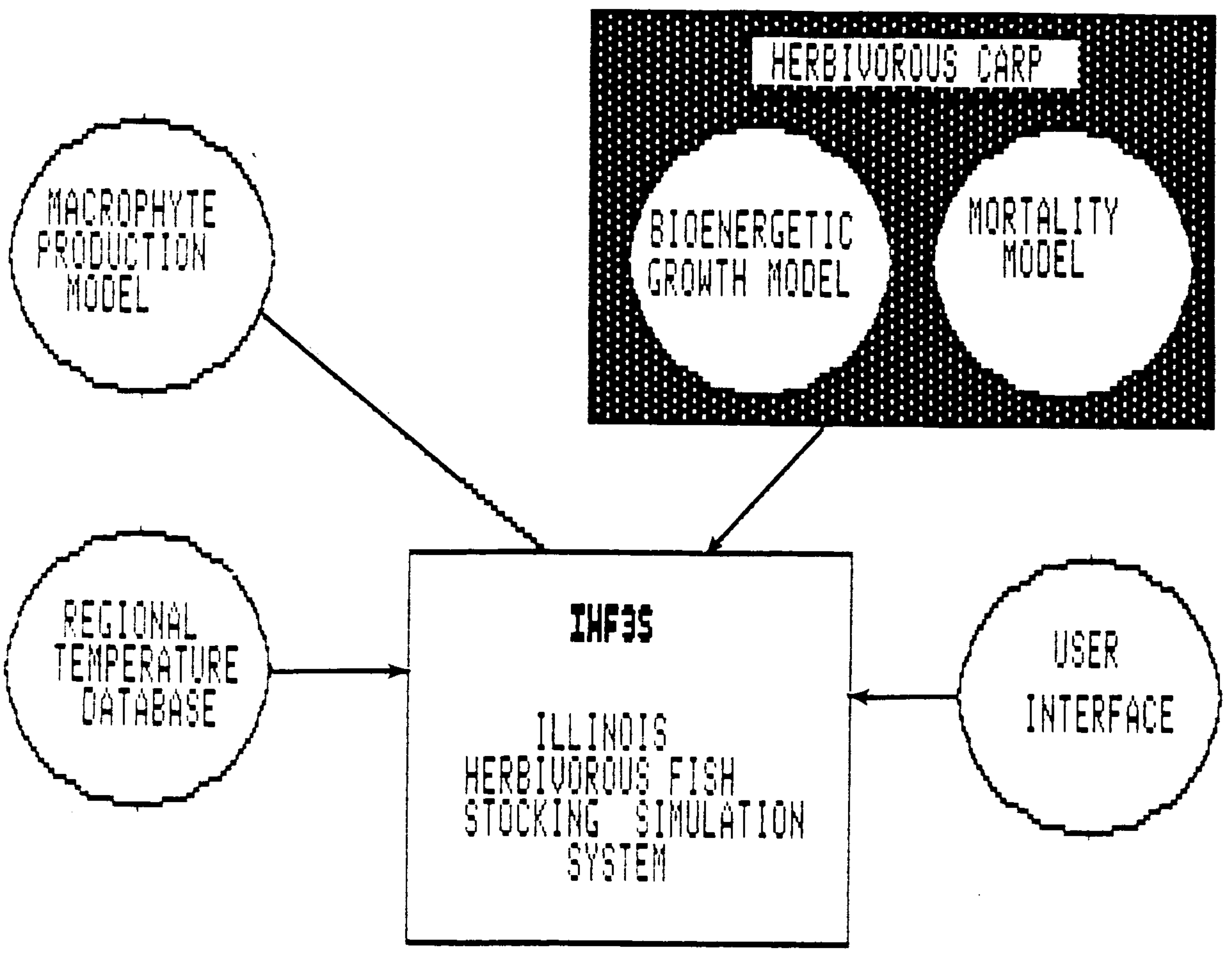


Fig. 2-46. Eradication of Myriophyllum spp. in Region 19.



System diagram for the
Illinois Herbivorous Fish Stocking Simulation System

Chapter 3

DESCRIPTION OF THE ILLINOIS HERBIVOROUS FISH STOCKING SIMULATION MODEL

OVERVIEW

The Illinois Herbivorous Fish Stocking Simulation System (IHF3S), used as the basis for our stocking recommendations, was developed during the last two segments of F-37-R. It has served as the ultimate integrator of our laboratory and field studies. Four distinct components comprise the IHF3S system:

(1) A bioenergetic growth model for the carp. Its primary function is to keep track of average daily consumption, growth, and size for each of the (up to three) separate stocking groups currently active in the simulation.

(2) A carp mortality model. This routine calculates fish mortality in each stocking group as a function of age, density, food supply, and water temperature, and it keeps track of the total number of active fish in each group.

(3) A macrophyte production model. The plant submodel simulates the growth and natural mortality of annual and/or perennial macrophyte species (or assemblages) and calculates various statistics relating to the performance of herbivorous carp during a particular model run.

(4) A regional temperature data base. The temperature data base provides the seasonal temperature regimes that drive the main submodels. Weekly mean temperatures are provided in a series of ASCII text files for each of 20 climatic regions in Illinois; these can be loaded by the user in any order to provide a comparison of stocking strategies under different climatic assumptions.

Each of the main system components interact under the control of, and with the user, by means of a set of subroutines referred to here as the "user interface" (see Model Implementation, this chapter). In this section we will briefly describe the basic relationships and equations incorporated into each of submodels as well as provide a short justification for our formulations and assumptions.

1. Bioenergetic Growth Submodel

This submodel calculates daily growth, average consumption, and average size for each of the stocking groups currently active in the simulation. A stocking group is a group of carp stocked on a particular simulation day, and it is treated as a unit throughout the simulation. Each stocking group is defined in terms of three properties: (a) its date of stocking; (b) the number of fish stocked; and (c) and their average size at stocking. Once a stocking group is activated by a routine which checks continuously for the occurrence of a operator-specified stocking date, the submodel calculates average values of growth, consumption, and size for the group at each time-step and makes them available to the other submodels in IHF3S.

Following the balanced energy equation the model estimates the growth of stocked fish as:

$$\text{GROWTH} = \text{INGESTION} - \text{EXCRETION} - \text{RESPIRATION} \qquad (1)$$

A. Ingestion (units = g ingested/g weight * day) is estimated from body size, temperature, plant species being eaten, and ploidy. Specifically, when food is not in short supply and fish are less than 15 kg, ingestion is estimated as:

$$\text{I} = \text{BWPD} * \text{SIZE} * \text{TC} * \text{PC} * \text{PLOIDY} * \text{FOOD CALORIC CONTENT} \qquad (3)$$

where (a) BWPD is the average proportion of body weight per day consumed by diploid grass carp at 20 C feeding on *Potamogeton crispus*;

(b) SIZE is fresh weight of the fish in grams;

(c) TC is a scaler from 0.0 to 1.0 representing the effect of temperature on ingestion rate (Wiley and Gorden 1984b) (Fig. 3-1) and is given by:

TC = 1/0.36778 * (ln temp * 0.52 + 1.1853) (3)

(f) PC is a correction factor which adjusts the consumption to reflect relative feeding rate differences for different plant species relative to Potamogeton crispus (Table 3-1).

(e) PLOIDY is 0.81 for hybrids, 0.91 for triploids, and 1.0 for diploid grass carp;

and (f) FOOD CALORIC CONTENT is 500 for fish less than 30 g, 1,000 for fish from 31 to 100 g, and is equal to the caloric content of the plant being eaten for fish exceeding 100 g in weight (Table 3-1);

BWPD is based on laboratory studies (Wiley and Gorden 1984b) and is set at 0.42 for fish less than 15 kg in size. This value is the average consumption rate at 20°C for Potamogeton crispus, the species we worked with most frequently in the laboratory and field (Table 3-1). PC then corrects BWPD for each plant species, TC corrects for temperature, and PLOIDY corrects for the ploidy of the fish.

Despite commonly encountered wisdom to the contrary, there is very little data to support the idea that consumption rate rapidly declines with body size in herbivorous carp. Our own work is the most rigorous available for the size range of 50-2500 g and shows little indication of a decline in consumption (Fig. 3-2). Studies with very large fish are virtually nonexistent. Chapman and Coffey (1971) reported a 50% reduction in consumption in penned individuals between the sizes of 313 g and 10.2 kg, and Shireman and Maceina (1980) estimated that 6+ kg fish ate only 26-28% of their body weight per day of Hydrilla in a Florida lake (measured rates for smaller fish feeding on hydrilla usually approach or exceed 100%). However, in the former study measurements were made in situ under conditions which raise doubts about the feasibility of obtaining accurate results; in the later study, consumption was not directly measured nor were influences of other confounding factors controlled. As a result, the best

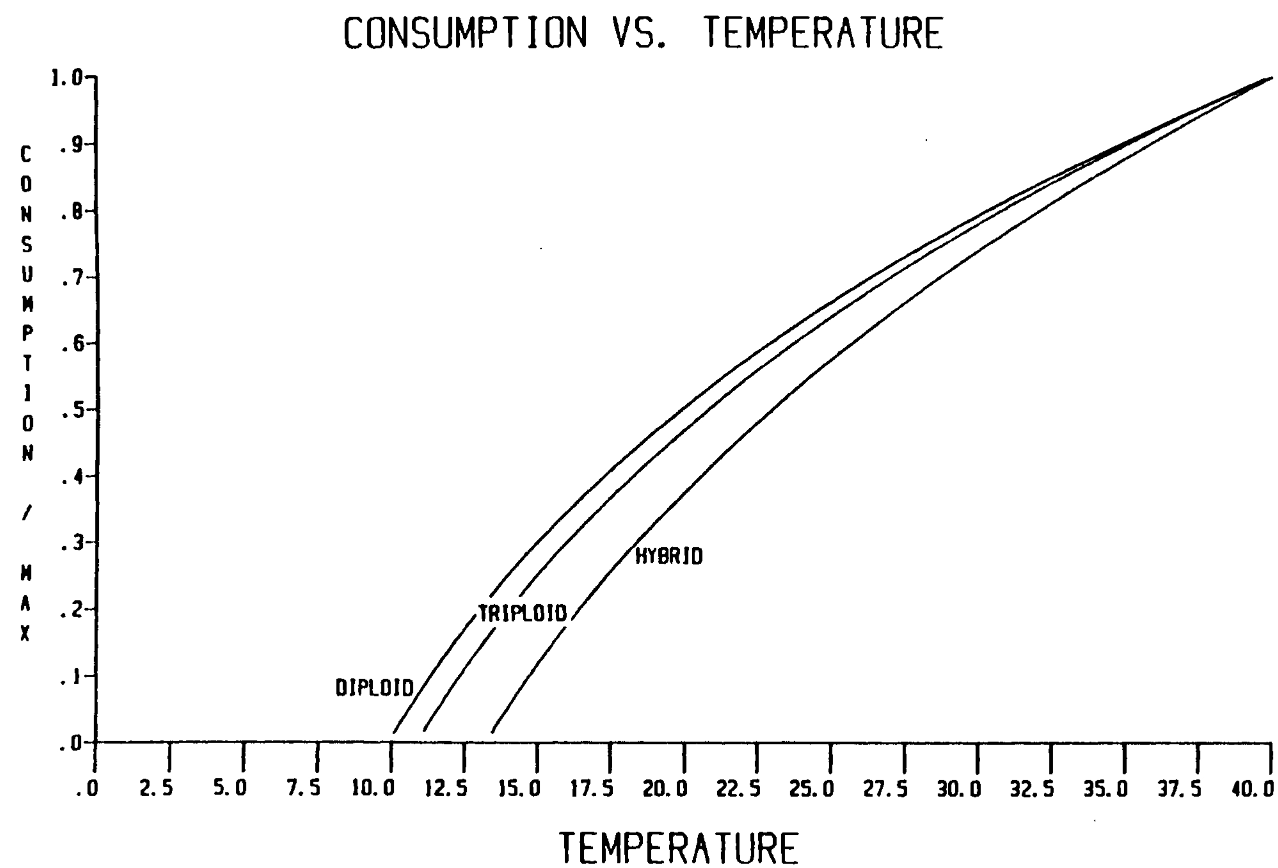


Fig. 3-1. Temperature correction factor (TC) for consumption (BWPD) versus temperature as modeled for three types of herbivorous carp.

Table 3-1. Fresh to dry weight ratios and caloric values (cal/g) of aquatic macrophytes (Wiley and Gorden 1984b, Chapters 1 and 2). Percent body weight per day (BWPD) is given at 20°C and for 500 g triploid grass carp.

Species	Rank	Cal/g wet weight	Cal/g dry weight	Fresh to dry weight ratio	% BWPD
Najas flexilis	1	517	3,390	0.16	51
Najas minor	2	328	3,640	0.10	47
Potamogeton foliosus	3	467	3,010	0.15	NA
Chara spp.	3	509	1,853	0.18	45
Elodea canadensis	4	430	2,208	0.24	52
Potamogeton pectinatus	5	658	3,603	0.09	37
Potamogeton crispus	6	304	3,774	0.10	42
Myriophyllum spp.	7	813	3,980	0.20	27
Ceratophyllum demersum	8	446	3,578	0.10	12

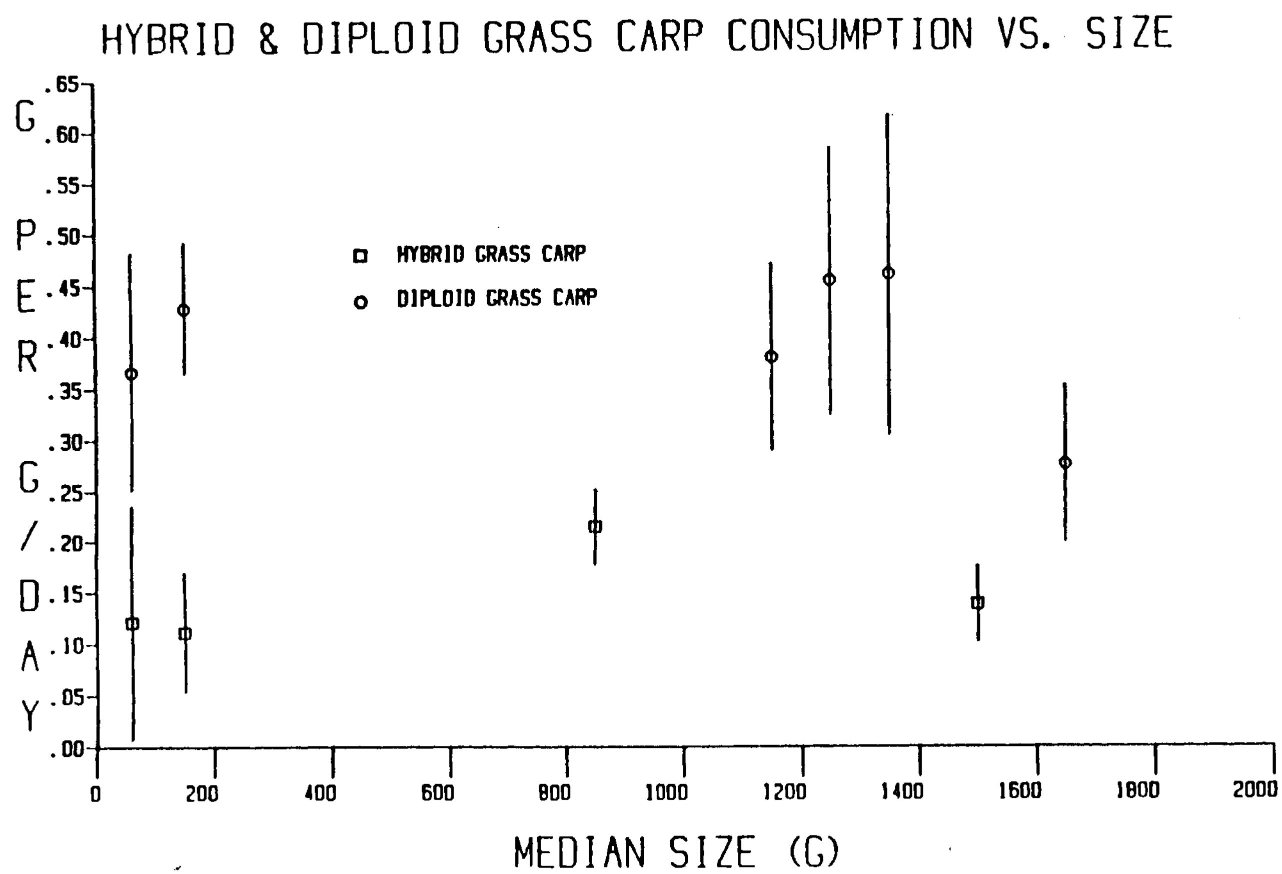


Fig. 3-2. Consumption (± standard deviation) by size class for hybrid and diploid grass carp. Based on laboratory feeding studies described in Wiley and Gorden (1984b).

that can be said is that there is some indication of a decline in consumption, but the data are insufficient to really describe the relationship between consumption and size with any accuracy. This being the case, we chose to make the simplest assumption we could about consumption and have treated it as a constant 42% of body weight (corrected to 20°C and _P. crispus_) for fish up to to 15 kg, reducing it to 21% of body weight for fish larger than 15 kg. Although obviously this cannot be very realistic, the error involved in this procedure will likely be no more biased than that from any more complicated but unfounded relationship we could assume.

Temperature, ploidy, and preference corrections were empirically derived from laboratory studies described in detail in Part II of this series of reports (Wiley and Gorden 1984b). The caloric content of the ingested material is set in the model using three size-related thresholds. For fish less than 30 g we assumed that they would be essentially invertivorous and, therefore, the caloric value of the food should be in the range of those typical of aquatic insect larvae and large zooplanktors. Fish weighing 30-100 g were considered to be in a transition stage, feeding on both plant and animal materials (Fisher and Lyakhnovich 1973; Shireman and Smith 1984; Wiley, unpublished data), and the caloric content of their food is set to a value intermediate between typical plant foods and animal tissues. When reaching 100 g, we assumed that the fish would be entirely herbivorous and the caloric content is simply the caloric content of the particular species of plant being ingested.

In situations in which the simulated plant biomass is too low to provide the estimated ration for a stocking group, the ingestion portion of the growth model compensates in two different ways depending on the level to which the plants are depleted. If there is some plant biomass available, the ingestion routine allocates all that is available equally between all current members of the stocking group. At each time-step, food is allocated to each active stocking group sequentially. The effect of this routine is to provide a partial daily ration and at the same time to reduce the plant population to zero ± the net plant growth for that time-step.

When the plant population is zero, ingestion is set to 5% of the estimated ingestion (Eq. 2). This caloric subsidy to the starving fish is an attempt to simulate the behavioral response of grass carp foraging in macrophyte-depleted environments, which we have observed repeatedly in the field and in the laboratory. In the absence of plants, these fish turn to copraphagy and to "mud-eating," presumably in an attempt to use whatever available organic carbon they can find. As a result of this reversion to a omnivorous diet, grass carp can remain in surprisingly good condition for a month or more in ponds that have been completely stripped of vegetation.

B. <u>Excretion</u> (units = cals/g fresh weight * day) is modelled as:

$$E = (1 - \text{ASSIMILATION} * k1) * k2 * \text{INGESTION} \qquad (4)$$

where (a) $\text{ASSIMILATION} = 0.054 * \text{TEMP}^{1.34} * \text{SIZE}^{-0.436}$;

(b) k1 is a variable which is normally equal to 1, but is set to

$$k1 = 1 + (0.2 + 0.2 * (\text{received ration}/\text{desired ration})) \qquad (5)$$

when only partial daily rations are available; received ration is the ration corrected for availability (see above), desired ration is the ration as calculated by Eq. 2.

(c) k2 is a coefficient (=0.97) used to calibrate the assimilation equation;

and (d) INGESTION is as estimated using Eq. 2 above and corrected for food availability.

Excretion here is taken to include fecal loss + urine loss + all other non-fecal losses. The assimilation equation was derived empirically from energy balance experiments described in Part II (Wiley et al. 1984b) and is adjusted by k2, the value of which was determined during the model calibration procedure (see below). Assimilation efficiency declines with increasing size (Fig. 3-3) and increases with increasing temperature (Fig. 3-4). Although it is likely that assimilation efficiency also varies with

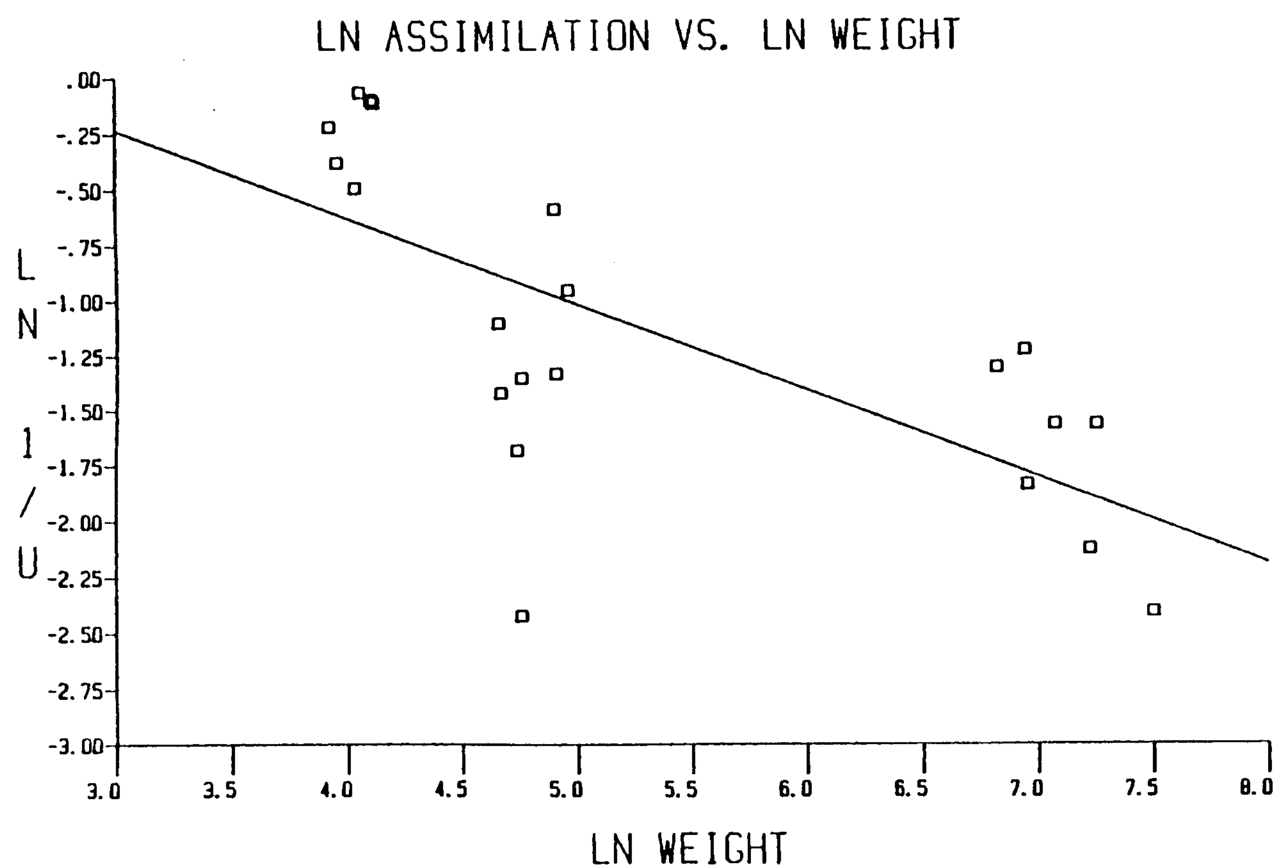


Fig. 3-3. Observed (points) and modelled (line) assimilation efficiency (1/U) as a function of weight.

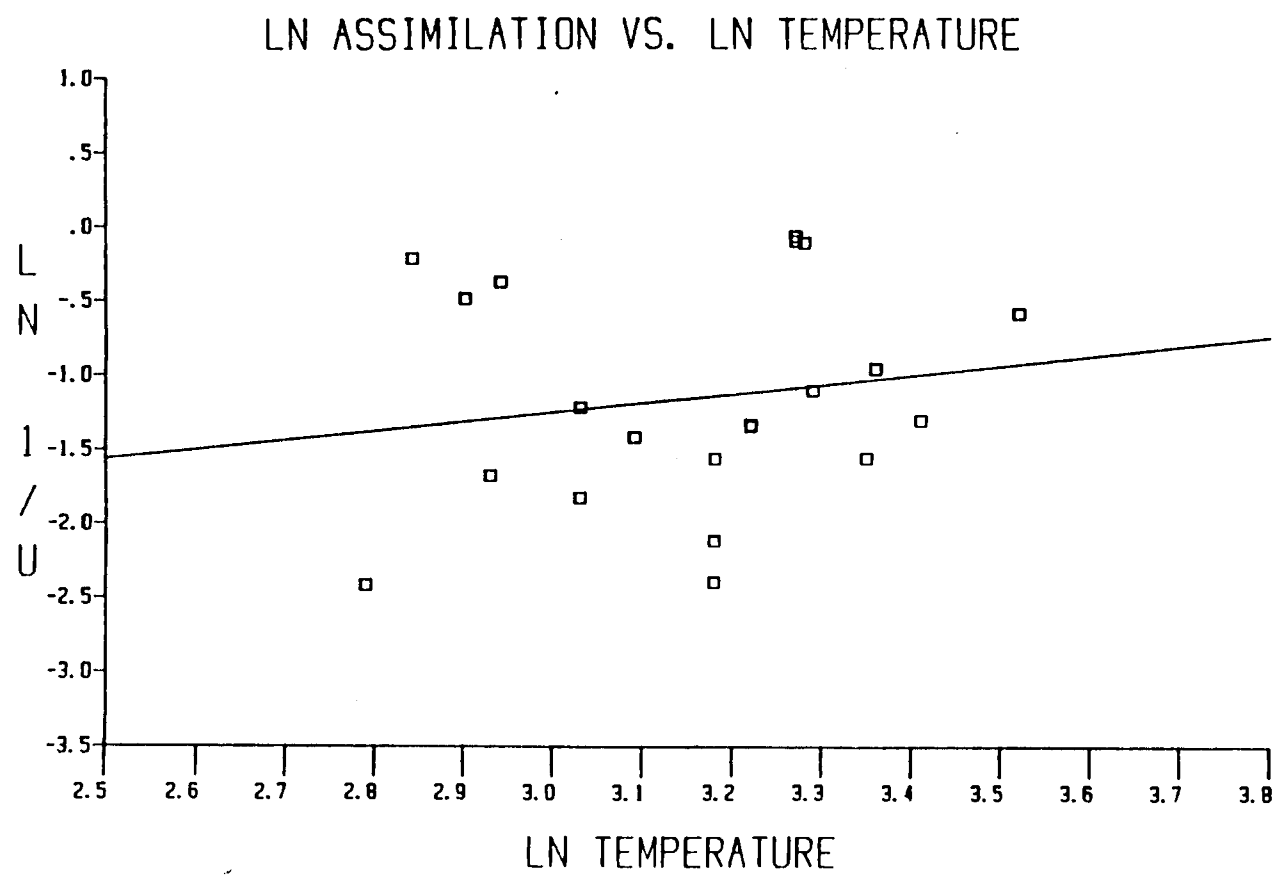


Fig. 3-4. Observed (points) and modelled (line) assimilation efficiency as a function of temperature.

the type of plant being eaten, there was so little data available that we ignored this source of variation.

k1 provides a means of implementing a " k-line" type relationship between ration size and growth efficiency (Paloheimo and Dickie 1966). When the carp receive lower than average rations (as estimated by Eq. 2), assimilation efficiency increases linearly with decreasing ration size. We used a maximum increase in efficiency of 20%, which seems reasonable given the types of ranges observed in other kinds of fish. However, no k-line relationships have ever been constructed for these herbivores and so this value might be in error.

C. <u>Respiration</u> (units = cals/g fresh weight * day) is modelled as:

$$R = (\text{STANDARD METABOLISM} * \text{ACTIVITY FACTOR} * \text{TEMP CORRECTION}) + \text{SDA} \quad (6)$$

where (a) STANDARD METABOLISM at 20°C is given by:

$$Q02 = 0.26 * \text{temp}^{0.645} \quad (7)$$

(b) ACTIVITY FACTOR is a multiplier between 1 and 2 scaled linearly to TC (see below).

(c) TEMP CORRECTION = 1/(exp(- 0.08868 + 1.8058 TEMP))

and (d) SDA is specific dynamic action and is given by:

$$\text{SDA} = 0.06 * \text{INGESTION} \quad (8)$$

Standard metabolism estimates are based on extensive laboratory data (Wiley et at. 1984b) and are corrected for body size and temperature (Fig. 3-5). The standard metabolism is then incremented by an activity multiplier up to a maximum of twice the basal rate. The multiplier was scaled by TC, which is the relative consumption rate with respect to temperature. Thus the basal metabolism is scaled up according to expected feeding activity. SDA costs are then estimated as 6% of the ingested calories and added to the active metabolism. We have used a value approximately 40% lower than average SDA's reported for insectivores (Brett and Groves 1979). This reduction was based upon the carbohydrate and protein composition of

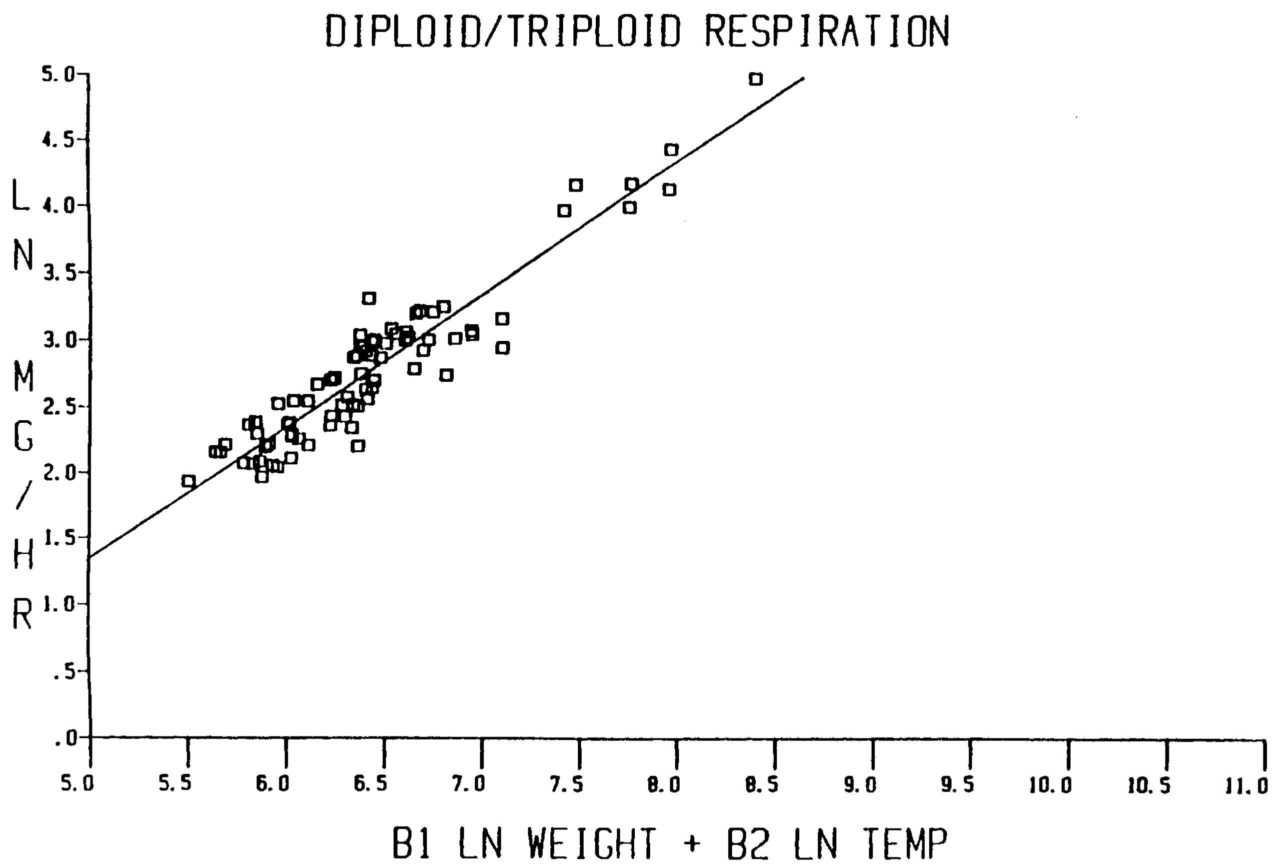


Fig. 3-5. Observed (points) and modelled (line) standard metabolism of grass carp as a function of weight and temperature (diploid and triploid carp combined).

plant material and the relative metabolic costs of processing protein and carbohydrate in vertebrates (Consolazio et al. 1963).

The bioenergetic submodel integrates each of these three rates (ingestion, excretion, and respiration) for each group of fish stocked on a given date and tracks the growth and average size of the group throughout the simulation or until the mortality model indicates all of the fish initially stocked in the group are dead.

2. Mortality Submodel

The mortality submodel estimates the number of fish remaining in each of the active stocking groups at each time-step. Since all recruitment is via stocking, the model must only be concerned with various sources of mortality. All mortality is modelled as an exponential function of population size. The total mortality rate for each stocking group is calculated as:

$$M = \text{PREDATION MORTALITY} + \text{STARVATION MORTALITY} + \text{WINTER MORTALITY} \quad (9)$$

A. Predation mortality (units = number/day) is modelled as:

$$M(\text{size}) = \text{MORTCOEF}(\text{age}) * N(j) * (1 - \text{WINTER}) \quad (10)$$

where (a) MORTCOEF(age) is calculated for fish < 300 g as:

$$\text{MORTCOEF}(\text{age}) = 0.4645 * 0.00714 \ln(\text{WEIGHT}) \quad (11)$$

and for fish > 300 g is set by age (Table 3-2);

(b) N(j) is the number of fish remaining in stocking group j

and (c) WINTER is a flag = 1 for water temperatures <8°C and = 0 for temperatures $\geq$8°C

Size- and age-related mortality coefficients provide the basic mortality schedule for the model and represent both predation and age-related probabilities of death. For fish <300 g, mortality estimates are based upon survivorship observed in a series of 20 experimental stockings from

1982 through 1984 (Wiley et al. 1984b). As might be expected, mortality rates declined exponentially with increasing size (Fig. 3-6), presumably because the grass carp became less and less vulnerable to largemouth bass. Mortality in ponds stocked with larger fish was usually very low (Table 3-3), although the oldest fish we worked with were 5-year olds. Mortality in older fish could only be estimated. Catch records from native waters (Gorbach 1961) provided some guidance but this clearly is an area of the model which presently can be implemented only by using an "educated guess." A source of mortality that logically belongs in this particular mortality component, but which we have not implemented, is fishing mortality. Experiences in other countries suggest that grass carp can become the target of a growing sport fishery (Buckley and Stott 1977, Sutton et al. 1977, Terrell and Fox 1979). Indeed, our own experience has been that grass carp in ponds with little or no macrophyte cover will strike at artificial lures. But the amount of data available on gear vulnerability and catch rates is so limited as to make any attempt to model this loss impractical.

B. <u>Starvation mortality</u> (units = number/day) is modelled as:

$$M(starv) = HUNGER * MORTCOEF(starv) * N(j)$$

where (a) HUNGER = 0 if available food > daily ration (Eq. 2)
otherwise, HUNGER = 1 - (available ration/daily ration)
(b) MORTCOEF(starv) = 0.00547/day
and (c) N(j) is the number of fish remaining in stocking group j.

Starvation mortality losses are a critical component in estimating the control potential of a particular stocking regime. Because these fish are being used to destroy their own food supply, they will routinely face the prospect of starvation. The rate at which they die under no or low food conditions will directly affect the length of time a single stocking can be expected to control a plant population. Unfortunately, there is little or no data directly bearing on this question. We have modelled starvation mortality as an exponential loss in which the rate coefficient is a linear

```
( ------------------------------------------------------------------)
(-------------------------------------------------------------------)
(             AQUATIC MACROPHYTE PRODUCTION SUBMODEL                )
(                      -IHF3S.NHS                                   )
( ------------------------------------------------------------------ )
( ------------------------------------------------------------------ )

                  ( AUXILLARY EQUATIONS)

: SETDDAY TEMP F@ ZERO F> IF  ELSE    ( calculates current degree-day)
   STEP   F* DEGDAY F@ F+ DEGDAY F!
             THEN ;

: GROWFIX DAY F@ FIXS 250 > IF        ( adjusts growthrate of fall cohort)
     GRFX F@ PGR1 F! ELSE 47 FLTS
     1000 FLTS F/ PGR1 F! THEN ;



                     ( RATE EQUATIONS )


: PG1 PLANT1 F@ PCC1 F@ F/ PGR1 F@ F*        ( growth rate for plant1 )
        PGR1 F@ FSWAP F- PLANT1 F@ F*
        P.GRO1 F! ;


:  PG2  PLANT2 F@ NFC1 F@ F/ PGR2 F@ F*     (   growth rate for plant2 )
       PGR2 F@ FSWAP F- PLANT2 F@ F*
P.GRO2 F! ;


: PGBOUND1 WTEM F@ FIXS 10 < IF ZERO      ( low temp check for plant1)
           P.GRO1 F! THEN ;

: PGBOUND2  WTEM F@ FIXS 20 < IF          ( low temp check for plant2)
          ZERO P.GRO2 F! THEN ;
```

```
: PM1  DEGDAY F@ MB21 F@ F*              ( plant1 mortality rate )
       SIN MB11 F@ F* MB01 F@ F+
                  PLANT1 F@ F*
       P.MORT1 F! ;


: PM2 DEGDAY F@ MB12 F@ F^ MB02 F@          ( plant2 mortality rate )
     F* PLANT2 F@ F* P.MORT2 F! ;



: PMBOUNDS1 DEGDAY F@ FIXS     800 < IF   ( temp check for plant1 mortality)
     ZERO P.MORT1 F! ELSE DEGDAY F@ FIXS
 3500 > IF
     ZERO P.MORT1 F! THEN THEN ;

:  PMBOUNDS2 DEGDAY  F@ FIXS 800 < IF      ( temp check for plant2 mortality)
ZERO P.MORT2 F! ELSE DEGDAY F@ FIXS
     10000 > IF ZERO P.MORT2 F!
     THEN THEN ;


: PRATE PG1 PM1 PMBOUNDS1 PGBOUND1 PG2      ( update all plant rate equations)
       PM2 PMBOUNDS2 PGBOUND2 ;


                      ( STATE EQUATIONS )


FVAR CONWTT 0
: TOTALCONSUMP ZERO CONWTT F!            ( sum consumption by stocking group)
        #GRPS @ 1 DO
  I CONWT F@ I FNUM F@ F* CONWTT F@
          F+  CONWTT F! LOOP ;

: P.STATE1 P.GRO1 F@ P.MORT1 F@          ( integration for plant1 )
   F- CONWTT F@ 10 FLTS F/
     P1SEL @ FLTS F* F- STEP
       F* PLANT1 F@ F+  ZCHECK1 PLANT1
       F! ;

: P.STATE2 P.GRO2 F@ P.MORT2 F@ F-        ( integration for plant2 )
CONWTT F@ 10 FLTS F/  P2SEL @
     FLTS F* F- STEP
```

```
    F* PLANT2 F@ F+  ZCHECK PLANT2 F! ;

: P.TOT PLANT1   F@ PLANT2   F@ F+  PTOT  ( calculate total plant biomass)
     F! ;

: PEAK  PTOT   F@ PEAKB F@ FSAV F<       ( update peak biomass variable)
      IF FRES FSWAP PEAKB F!
      ELSE THEN ;

: PSTATE TOTALCONSUMP P.STATE2 P.TOT    ( update all plant state equations )
                  PEAK ;
```

```
( ---------------------------------------------------------------------- )
( ---------------------------------------------------------------------- )
(              AUXILLARY AND RUN-TIME SUBROUTINES                         )
(                    -IHF3S.NHS
( ---------------------------------------------------------------------- )
( ---------------------------------------------------------------------- )

: ZCHECK FSAV ZERO FSWAP F< IF ZERO F*     ( set negative # to zero )
         ELSE FRES THEN ;


: ZCHECK1 FSAV ZVAR F@ FSWAP F<= IF ZVAR   ( set to zvar if < zvar )
        F@ ELSE FRES THEN ;



: STEP STP F@ ;                            ( fetch step size )

: YEARCHECK DAY F@ 364 FLTS F< ;           ( check for end of year )


: RESETYEAR O FLTS FDUP DAY F! WDAY F!     ( setup for new year )
            O WEEK ! YEAR @ 1 + YEAR !
            ZERO FDUP DEGDAY F! FDUP
            CUMCON F!
                      ;


: PERCENT ( PROP -> % ) 100 FLTS F* ;        ( convert to percent )


: READTEMP 1 1 " TEMP FILE? " S. GNM   ( read in temp data from disk )
    OPN  NME RD  WORD
         52 O DO
             FINPUT FIXS
            DUP . CR I TMPWEEK !
              LOOP
         NME CLS ;

: SET FINPUT F! ;             ( set flp variable: <name> SET <value> )


: SEE F@ F. CR ;                    ( display flp variable )
```

```
: SETDAY
          ( SETS DAY AND WEEK )
          DAY F@ STEP F+    DAY F!
          WDAY F@ STEP F+ FDUP WDAY F!
                   EIGHT FSWAP F>=
          IF ONE WDAY F! WEEK @ 1 +
             WEEK !
          THEN ;


: SETTEMP
          ( SETS TEMP )
              WEEK @ TMPWEEK @ FLTS
             TEMP F!  ;


FVAR WT1 .93095
FVAR WT2 3.06
FVAR WTEM 0
: SETWTEMP TEMP F@ WT1 F@ F* WT2 F@      ( set water temp  )
       F+ WTEM F! ;

FVAR FINESTP .5
: SETSTP TEMP F@ FIXS 8 < IF             ( set time-step by temp )
         4 FLTS STP F! ELSE
      STPO F@
STP F!    THEN ;

: TYPES "  DIPLOID" ;                    ( define string )

: DIPLOID 0 TRIP? ! C84 F@ C24 F!        ( set model to simulate diploids )
                    C85 F@ C25 F!
                    C86 F@ C26 F!
 "  DIPLOID" TYPES S! ;

: TRIPLOID 1 TRIP? !   C87 F@ C24 F!     ( set model to simulate triploids )
                        C88 F@ C25 F!
                     C89 F@ C26 F!
   " TRIPLOID" TYPES S!
          ;
```

```
FVAR TRCONCV .90
: TRIPCHK  TRIP? @ 1 =                  ( if triploid reduce consumption)
               IF TRCONCV F@ F*
               THEN ;


               (    DISPLAY  WORK     )

:  FPRINT         5 0 VHTAB  INVERSE        ( table of current energetic values)
 " DAY=  " S. DAY SEE
 " WEEK= " S.          WEEK @ .
  " TEMP=  " S. TEMP SEE  NORMAL
 #GRPS @ 1 DO
   I . " NUMBER=  " S. I FNUM   SEE
   I . " SIZE =  " S. I SIZE SEE
               LOOP
   " RTM=        " S. RTM SEE  CR
                CR INVERSE CONWTT SEE
PAVAIL SEE  FNUM SEE " HUNGER=" S.
HUNGER SEE NORMAL ;


: PDRAW WEEK @ FLTS YEARW    F/ YEAR @     ( plot value of variable pointed
FLTS F+                                      to by VPLOT   )
  VPLOT @ F@ 1000 FLTS F/ ULINE ;

FVAR #YEAR 10

: GINIT TURTINIT 10 YTICS ! 300 FLTS    ( initialize graphic page)
               YMAX
       F! 10 XTICS ! #YEAR F@ XMAX  F!
    F! CLEAR SETSCALE AXES        WHI
  XTITL " YEARS AFTER STOCKING"
    G. TITL1 " HERBIVOROUS FISH STOCKING MODEL " G.
          29 175 MOVETO ;

             ( title strings )
: BLK "      " S. ;
: TLE1 " YEAR FNUM   SIZE" S. ;
: TLE2 "  KG/HEC  CON%PROD      " S. ;
: TLE3 "  AVEPEAK   AVEBIOMASS  PEAK" S.     ;
: ISEE F@ FIXS . ;

FVAR CUMSIZE 0
FVAR CUMDAY 0
```

```
FVAR 3AVEPK 0
FVAR AVEPK 0
: AVEPEAK PEAKB F@ AVEPK F@ F+ FDUP ( calc average reduction in peak to date)
    AVEPK F! ( YEAR @ 4 = ) IF ( 3AVEPK
  F! ) ELSE ( FIXS DROP ) THEN
     AVEPK F@ YEAR @ FLTS F/ F.     ;

: AVERAGE PTOT F@ CUMSIZE F@ F+          ( calc mean biomass to date )
  CUMSIZE F! STP F@ CUMDAY F@ F+
  CUMDAY F! ;

: AVEBIO CUMSIZE F@ CUMDAY F@ F/ F. ;    ( calc mean biomass for year )


0 VARIABLE PRINT?
: PRINT_ON 1 PRINT? ! ;                   ( turn on printer)

: TITLEHEAD                          ( make title line for output )
            PRINT?  @ 1 = IF 1 PR# THEN
   TLE1 TLE2 TLE3 CR
     ;

10 1 DIM D.CODE
10 1 FDIM SI#
10 1 FDIM SISIZ

: SICHECK YEAR @ 1000 * DAY F@ FIXS +    ( put in stocking group if date
    #GRPS @ 1 DO  DUP                      matches stockin coded date )
    I D.CODE @ = IF I SI# F@ I FNUM
       F! I SISIZ F@ I SIZE F!
      THEN LOOP ;


: SETUP HOME  " ENTER # OF STOCKINGS"     ( get set up values from user )
  S. INPUT 1 + DUP #GRPS ! 1 DO
         " ENTER " S. CR
" NUMBER SIZE DAY YEAR " S. CR
" FOR  STOCKING " S. I . INPUT INPUT
INPUT INPUT
 1000 * + I D.CODE ! FLTS I SISIZ F!
  FLTS I SI# F! CR LOOP ;

FCON HUND 100
FVAR TOTALIN 0
: COMPUTESI ZERO TOTALIN F!               ( code stockin dates)
```

```
          #GRPS @ 1 DO
   I SI# F@ I SISIZ F@ F* HUND F/
   TOTALIN F@ F+ TOTALIN F! LOOP
            ;

: CPRINT1 YEAR @ . BLK FNUMR ISEE  BLK     ( output year results to table)
  SIZE ISEE BLK FNUMR F@ SIZE F@ F*
  HUND F/ FIXS . BLK
  CUMCON F@ P.PROD  F@ F/ 100 FLTS F*
   FIXS . BLK BLK
   AVEPEAK BLK AVEBIO BLK PEAKB F@ F. CR
  ;


44 VARIABLE YTAB
: STK$ "      " ;                          ( define blank string )

: SS$ STK$ SCLR STK$ BASC ;                ( write blanks to graphics page )

: STATS 176 35 GTAB " YR  #  SIZE " G.     ( put info on graphics page )
   44 YTAB !   #GRPS @ 1 DO
  176    YTAB @ GTAB I D.CODE @ 1000 /
 STK$ SCLR      STK$ BASC  G. I
 SI# F@ FIXS 200 YTAB @ GTAB SS$ G. I
 SISIZ F@ FIXS 222 YTAB @ GTAB SS$ G.
     YTAB @ I 6 * + YTAB ! LOOP ;

: PRINT_OFF 0 PRINT? ! ;                    ( turn off printer )


FVAR MPEAK 162103

: ENDSTAT 36 35 GTAB " % REDUCTION IN PEAK:"  ( put performance info on graph)
    G. 81 44 GTAB " 10 YR AVE=" G. AVEPK
    F@
   YEAR @ FLTS F/ MPEAK F@ F/
     STK$ SCLR HUND F* HUND FSWAP F-
   FIXS STK$ BASC G. 81 51 GTAB
   " 4 YR AVE=" G. 3AVEPK F@ 4 FLTS F/
     MPEAK F@ F/ STK$ SCLR HUND F* HUND
    FSWAP F- FIXS STK$ BASC G. ;


FVAR HALF .5
```

```
: RND->I  HALF F@ F+ FIXS ;          ( round flp variable to integer)


                ( do a complete simulation)

: CRUN TITLEHEAD FNUM F@ FNUMR F!      (  run  with  graphic  output  of  plant
biomass)
   COMPUTESI CPRINT1
   CR TITL2 "     " G.
     TYPE$ G. " S IN " G. NME G.
      TITL3 "   TOTAL STOCKED=" G.
       STK$ SCLR
TOTALIN  F@ RND->I STK$
        BASC STK$ G. " KG/HEC " G.

           STATS

      0 0 IPLOT
   BEGIN CAUX CRATE CSTATE SICHECK
         ( CPRINT )  PDRAW
              AVERAGE
  DAY F@ 364 FLTS F< IF  YEAR @ 1 +
    YEAR ! CPRINT1  ZERO CUMCON F!
     1 WEEK ! ZERO DAY F!
     ZERO PEAKB  F!
     5000 FLTS PLANT2 F! ZERO P.PROD2
     F! ZERO P.PROD F!
      ZERO P.PROD1 F! ZERO DEGDAY
  F! 0 ELSE 0 THEN YEAR @ #YEAR F@
  ONE F-     FIXS >
     IF 1 ELSE   THEN END ENDSTAT ;


: CRUN2 TITLEHEAD FNUM F@ FNUMR F!   ( run with table output of energetics)
               CPRINT1
   CR TITL2 "     " G.
     TYPE$ G. " S IN " G. NME G.
      TITL3 "     STOCKED AT " G.
       STK$ SCLR
 FNUM F@ SIZE F@ F* HUND F/ FIXS STK$
        BASC STK$ G. " KG/HEC " G.

           STATS

      0 0 IPLOT
```

```
   BEGIN CAUX CRATE CSTATE SICHECK
           PDRAW     FPRINT
              AVERAGE
  DAY F@ 364 FLTS F< IF  YEAR @ 1 +
    YEAR ! CPRINT1  ZERO CUMCON F!
     1 WEEK ! ZERO DAY F!
     ZERO PEAKB  F!
     5000 FLTS PLANT2 F! ZERO P.PROD2
     F! ZERO P.PROD F!
      ZERO P.PROD1 F! ZERO DEGDAY
     F! O ELSE O THEN YEAR @ 9 >
     IF 1 ELSE   THEN END ENDSTAT ;

              ( reset subroutines)
: CRESET
ZERO TSCALE F!
ZERO WSCALE F! ZERO FDUP FDUP WSCALE2 F! WSCALE F!
         ZERO VBERT  F!
ZERO FDUP FDUP QW F! QW2 F! QW3 F!
     ZERO AGE    F!
       O   FLTS DAY F!
         60  FLTS SIZE F!
       154 FLTS AGED F!  O YEAR !
       1 WEEK !
       29 175 HPOSN ;


FVAR P1START O
FVAR P2START 5000
: RESET ZERO CRESET
            P1START F@ PLANT1 F!
    273 FLTS 1000 FLTS F* PCC1 F!
    4 FLTS 100 FLTS F/ GRFX F!
    O YEAR !
    ZERO P.PROD1 F! ZERO TSCAL F!
    ZERO PEAKB F!  ZERO WDAY F!
    ZERO DEGDAY F!  ZERO P.PROD2 F!
    ZERO P.PROD F! P2START F@ PLANT2 F!
    200 FLTS 1000 FLTS F* NFC1 F!
    PTOT VPLOT !
    ZERO CUMDAY F! ZERO AVEPK F!
      #GRPS @ 1 DO ZERO I FNUM F!
         ZERO I SIZE F! ZERO I CUMCON
         LOOP   ;
```

```
: DUMPG 1 PR# CR " G" S. CR 0 PR# ;        ( dump graphic to printer )
: DUMPS 1 PR# CR " S" S. CR 0 PR# ;        ( dump text page to printer)
```

```
( ------------------------------------------------------------------)
(-------------------------------------------------------------------)
(                GLOBAL VARIABLE INITIALIZATIONS                    )
(                        - IHF3S.NHS                                )
(-------------------------------------------------------------------)
(-------------------------------------------------------------------)

( note:  these definitions must be loaded prior to compilation of submodels)


FVAR TEMP 0
10 1 FDIM CONSUMP 0
10 1 FDIM FECES   0
10 1 FDIM RESPIRE 0
10 1 FDIM SIZE    60
10 1 FDIM CUMCON  0
10 1 FDIM CONWT
FVAR QW2 0
FVAR DEGDAY 0
FVAR QW3 0
FVAR DAY     0
FVAR TSCALE  0  ( TEMP SCALER FOR RES )
FVAR WSCALE  0  ( WGHT SCALER FOR RES )
FVAR VBERT   0  ( AGE CORRECT FOR EXC )
FVAR QW      0  ( WINBERGS LITTLE Q )
FCON ZERO   0.0
FVAR AGE     0  ( AGE IN YEARS )
FVAR AGED   154 ( AGE IN DAYS )
FVAR TMPWEEK 0  ( AVE WEEKLY TEMP )
10 1 FDIM FKILL 0
10 1 FDIM FNUM 0
FVAR MC1 .0022
FVAR MC2 .0001
FVAR MC3 .0030
10 1 FDIM FMORT 0
FVAR TARGET 2000000
FVAR STARVE .05
FVAR WDAY  1
FVAR WSCALE2 0
FVAR WSCALE3 0
59 1 DIM TMPWEEK
1 VARIABLE WEEK
0 VARIABLE YEAR
FVAR RTM    1.9 ( ROUTINE METAB INCR )
1 VARIABLE #GRPS
```

```
FCON ZERO  0.0
FVAR STP     1.0
FVAR C1    -.08034    ( CONSUMP COEFF )
FVAR C2    1.14       ( CONSUMP COEFF )
FVAR C3    -3.06      ( CONSUMP COEFF )
FCON C4    2.494
FCON EIGHT 8.00
FCON C5    -.163
FCON C6    .003
FCON T1    .2213
FCON T2    -.0013487
FCON T3    17.56
FCON TWO   2.0
FVAR C10   .05   ( URINE LOSS AS % CONSU
                 MPTION )
FCON C11   0.55
FCON C12  -.08868
FCON C13 1.805759
FCON PDRY  .12   ( WET TO DRY PLANT)
FCON FDRY   .25  ( WET TO DRY FISH )
FCON CARPC  980.
FVAR W1     .645  ( RESPIRA  COEFF )
FVAR W2  .02599   ( RESPIRA  COEFF )
FVAR W3     .0259 ( RESPIRA  COEFF )
FVAR C24    .52  ( DTC COEFF )
FVAR C25  -1.1853 ( DTC COEFF )
FVAR C26   .36778 ( DTC COEFF )
FVAR TRIP?   0    ( TRIPLOID FLAG )

FVAR C84   .52  ( DIPL DTC COEFF )
FVAR C85  -1.1853 ( DIPL DTC COEFF )
FVAR C86 .36778 ( DIPL DTC COEFF )
FVAR C87 .499 ( TRIP DTC COEFF )
FVAR C88 -1.19 ( TRIP DTC COEFF )
FVAR C89 .3049 ( TRIP DTC COEFF )

FCON VB1      -.366
FCON VB2      3.134
FCON VBCORR  0
FCON ONE      1.0  ( 1.0 )
FCON O2CONV  82.2 ( FROM MG O2 TO CAL )
FCON FCONV   2850. ( FECES DW TO CAL )
FCON PCONV   250. ( PLANT FW TO CAL )
FCON YEARW   52  ( WEEKS PER YEAR )
```

```
FVAR PLANT1 55000
FVAR P.GRO1 1 ( GROWTH RATE )
FVAR P.MORT1 1 ( MORTALITY RATE )
FVAR MB01  .06552 ( MORT COEFF B0 )
FVAR MB11 -.0676 ( MORT COEFF B1 )
FVAR MB21 .0022 ( MORT COEFF B2 )
FVAR MB31   1  ( MORT COEFF B3 )
FVAR PCC1   390 ( MAX BIOMASS )
FVAR PGR1  .047 ( GROWTH COEFF )
FVAR DEGDAY 0   ( CUM DEGREE DAYS )
FVAR P.PROD1 0  ( CUM PROD PLANT 1 )
FVAR GRFX   .04 ( LATE PC GRTH RATE )

FVAR PLANT2 19
FVAR P.GRO2 1  ( GROWTH RATE )
FVAR P.MORT2 1 ( MORTALITY RATE )
FVAR MB02  1.32E-13 ( MORT COEFF B0 )
FVAR MB12  3.302 ( MORT COEFF B1 )
FVAR MB22  .0022 ( MORT COEFF B2 )
FVAR MB32    1   ( MORT COEFF B3 )
FVAR NFC1  170000 ( MAX BIOMASS )
FVAR PGR2   .100   ( GROWTH COEFF )
FVAR P.PROD2  0   ( CUM PROD PLANT2 )
FVAR P.PROD 0 ( CUM PROD PLANTS )
FVAR PTOT 0 ( TOTAL PLANT BIOMASS )
FVAR ZVAR 3500.0
FVAR PEAKB  0
FVAR TSCAL 0
FVAR RTMB  1
FCON MAXACT 1.06 ( %BWD CONC AT 35 C )
FVAR STPO 1.00 ( BASE STEP TIME )
FVAR STARVEKILL .003
FVAR PCONV1 300
FVAR PCONV2 543
0 VARIABLE P1SEL
0 VARIABLE P2SEL
FVAR P2CRATE .75 ( PLANT2 CONSUMP INCR )0 VARIABLE STARV?
0 VARIABLE VPLOT
FVAR WINTERKILL .00022
FVAR MRTC1 -.00705
FVAR MRTC2  .04645

11 1 FDIM MORT.TAB
DLOAD LOADMORT
FVAR CMIN .65
```

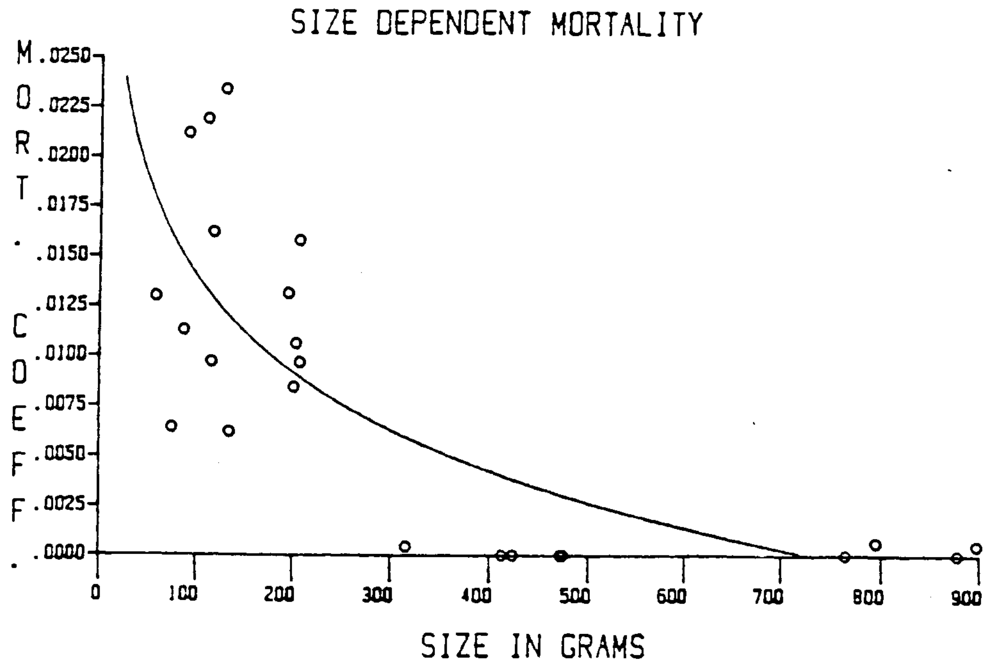


Fig. 3-6. Observed (points) and modelled (line) survivorship of stocked herbivorous carp as a function of size.

Table 3-2. Age-specific mortality coefficients used in the grass carp mortality submodel.

Age of fish	Mortality coefficient
2	0.00021
3	0.00021
4	0.00014
5	0.00040
6	0.00100
7	0.00100
8	0.00100
9	0.00100
10	0.00100
11	0.00100
12	0.00100

Table 3-3. Overwinter mortality during field trails, 1981-1983.

Fish	Type	Year class	Winter	Number Stocking	Number Census	% loss	Mean weight in fall (g)
Hybrid	(2N,3N)	1980	1980-81	364	279	27	18
Hybrid	(2N,3N)	1980	1981-82	31	31	0	279
Hybrid	(2N,3N)	1980	1982-83	27	26	4	591
Hybrid	(3N)	1981	1982-83	56	53	5	279
Hybrid	(3N)	1981	1982-83	77	76	1	172
Grass carp	(3N)	1981	1982-83	37	37	0	478

function of the degree of food shortage. On the basis of our general experiences with holding these fish in the laboratory, we set the mortality coefficient at zero food availability in such a way as to give an average time to death of 6 months. However, because the mortality is exponential with respect to number of fish, the time required for all fish present to starve to death approaches 2 years (Fig. 3-7). The relative accuracy of this simple exponential expression will be impossible to evaluate until some experimental data on starving fish become available.

C. Winter mortality (units = number/day) is modelled as:

$$M\ (\text{winterkill}) = \text{MORTCOEF}(\text{winter}) * \text{WINTER} * N(j) \qquad (13)$$

where (a) MORTCOEF(winter) is determined by age from Table 3-2;

(b) WINTER is a flag set to 0 from April to December and to 1.0 from December to April;

and (c) N(j) is the number of fish remaining in stocking group j

Winter mortality rates were observed from 1981 through 1983 in INHS experimental ponds (Table 3-3). Mortality was usually low with the exception of very small fish. In the model, winter mortality substitutes for size-related mortality when water temperatures are below 8°C.

3. Macrophyte production submodel

The macrophyte production submodel estimates growth and mortality, current standing crop, maximum biomass, and percent reduction in biomass as a function of temperature, cumulative degree-days, and carp foraging. Two simple temperature-driven general plant models are implemented, one for annual species and perennials with overwintering vegetative reproductive structures and one for perennial species with overwintering biomass in the form of shoots and vegetative reproductive structures. Either or both can be run in any simulation. Parameter estimates for each of these general models are loaded at the time of initialization to simulate any one of five types of plant population: (1) *Potamogeton crispus*/*Najas flexilis*, (2)

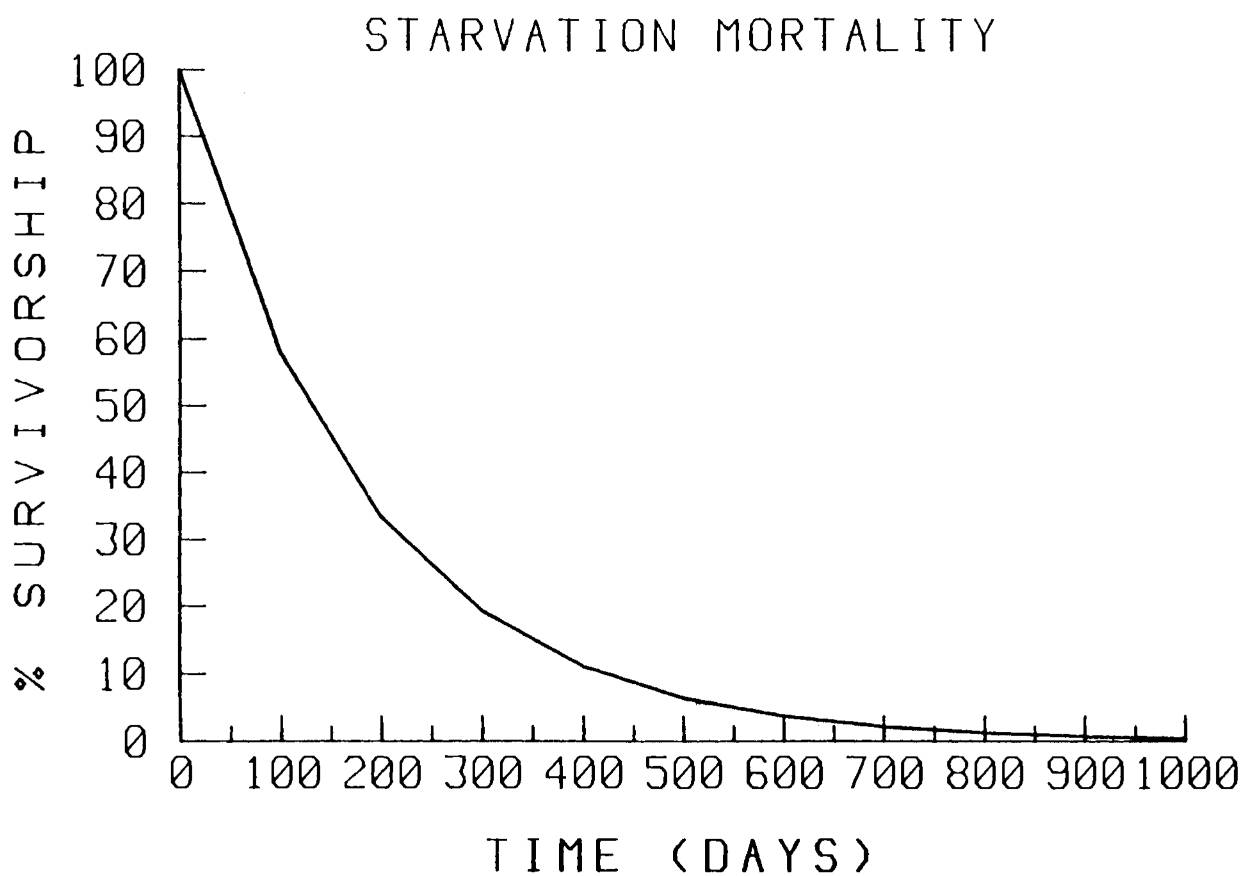


Fig. 3-7. Starvation mortality as implemented in the grass carp mortality submodel. Average time to death for starving fish is 6 months.

Potamogeton pectinatus/Najas spp., (3) Myriophyllum spp., (4) Elodea canadensis, or (5) Ceratophyllum demersum. Of these, P. crispus is perennial with overwintering shoot biomass and the rest are annual species (Najas spp.) or perennials with overwintering vegetative reproductive structures. Thus, P. crispus and/or any other assemblage can be simulated in a given run of the model.

Because the overall stocking model must be run with a minimum amount of site-specific data, our goals in modelling these plant populations were limited to providing as accurately as possible (a) correct phenologies for each species, (b) reasonable production rates, and (c) realistic biomass peaks. To that end we have used as our production model the simple relationship:

$$dPLANT/dt = GROWTH - NATURAL\ MORTALITY - GRAZING\ MORTALITY \qquad (14)$$

Growth of macrophyte populations (units = $g/m^2 * day$) is modelled identically for both annuals and perennials:

$$GROWTH = TEMPSWITCHg * G * PLANTS * (1 - PLANTS/PCC) \qquad (15)$$

where (a) TEMPSWITCHg is a flag (1 or 0) indicating temperatures are high enough to allow plant growth. Values vary by species and are given in Table 3-4;

b) G is an instantaneous growth rate (1/day) determined empirically for each species from field net-shoot production studies (Table 3-4);

(c) PLANTS is the current biomass per square meter (g dry weight);

and (d) PCC is the asymptotic maximum macrophyte density (carrying capacity) (Table 3-4).

When temperatures are high enough for plant growth (TEMPSWITCHg = 1), macrophyte production is treated as being exponential with respect to total biomass, moderated by a simple density-dependent feedback loop which constrains populations to levels below an asymptotic maximum density (PCC).

Table 3-4. Temperature threshold, growth rate, and carrying capacity of each macrophyte assemblage simulated.

	Temperature threshold (°C)	Growth rate Growth rate (g/g * day)	Carrying capacity (g dry wt./m^2)
Potamgeton pectinatus/ *Najas* spp.	20	0.100	200
Potamogeton crispus/ *Najas flexilis*	10,20	0.047,0.058	390,170
Elodea canadensis	18	0.125	500
Ceratophyllum demersum	19	0.090	200
Myriophyllum spp.	20	0.054	300

The instantaneous growth coefficient (G) is constant and was given the mean value observed in INHS field studies of each species (Table 3-4). PCC for each species was set to the highest density known for that species in Illinois. This ensures that the model will always produce average biomass concentrations which are lower than isolated, known maxima (Table 3-4). No attempt has been made to model variations in growth rate due to turbidity or nutrient concentrations, because such detail would require an unacceptably large amount of site-specific data, as well as an explicit modelling of co-existing phytoplankton populations. Attempts were made to add temperature and seasonal variability to the growth coefficients, but statistical analyses of temperature (and degree-day) dependencies of field growth rates indicated a very high degree of variability and few significant trends (e.g., Figs. 3-8 and 3-9). This variability undoubtedly represents the complex interaction of a number of local controlling factors beyond the scope of a state-wide management model. In the face of this variability, the use of a mean growth rate seems the least objectionable approach.

<u>Natural mortality</u> (units = grams m^2 * day) is modelled as:

$$M(natural) = M * PLANTS * TEMPSWITCHm \qquad (16)$$

where (a) M is an instantaneous mortality coefficient which varies seasonally as a function of cumulative degree-days;
(b) PLANTS is the species biomass per square meter;
and (c) TEMPSWITCHm = 1 when the temperature is above a set threshold.

Natural mortality is used in our model to control biomass phenology and is expressed as a function of cumulative degree-days. For annual species and perennials with overwintering vegetative reproductive structures, the general function used was:

$$M = a * DEGDAY^b \qquad (17)$$

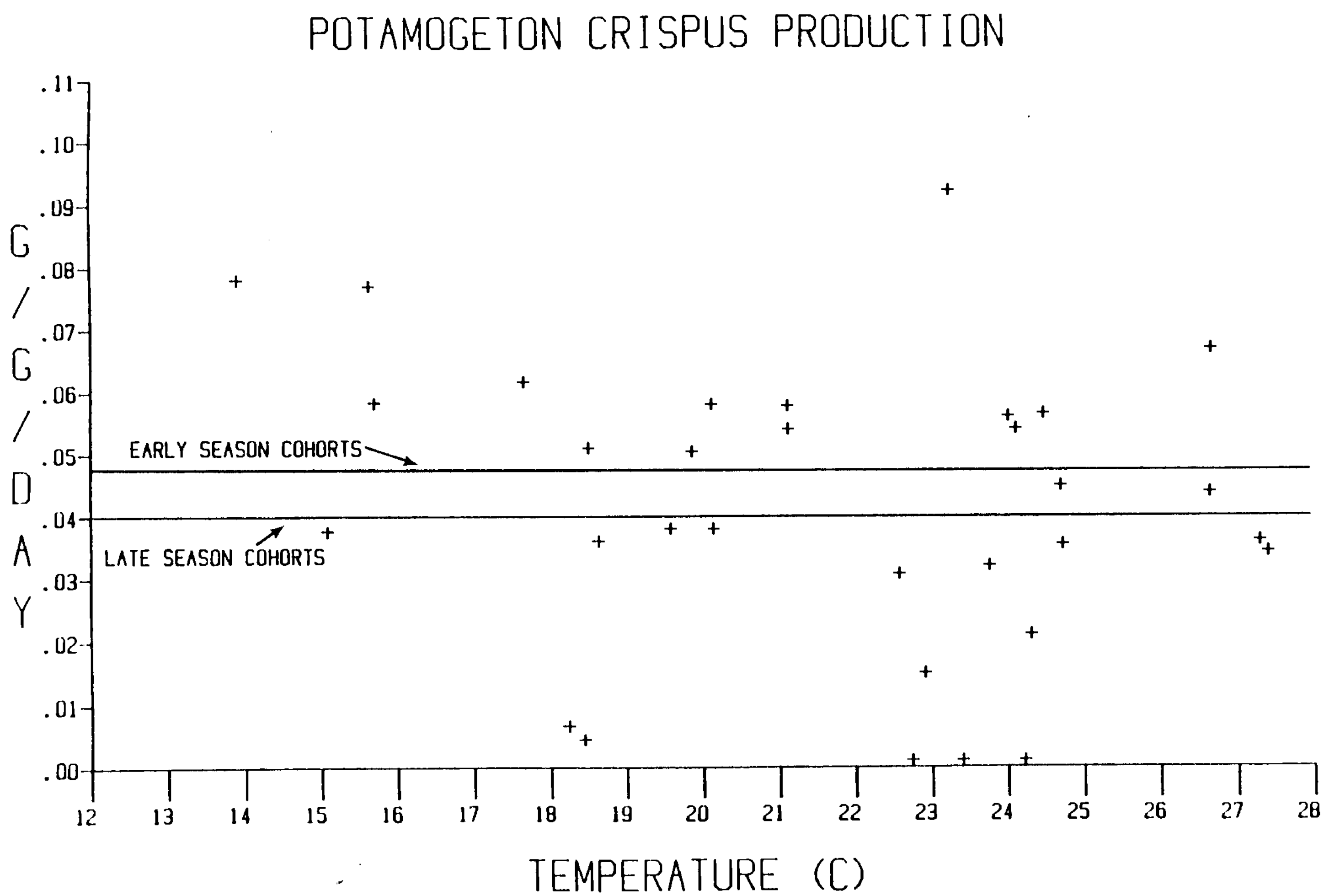


Fig. 3-8. Observed (points) and modelled (line) <u>Potamogeton crispus</u> production (g/g * day) as a function of pond temperature (°C).

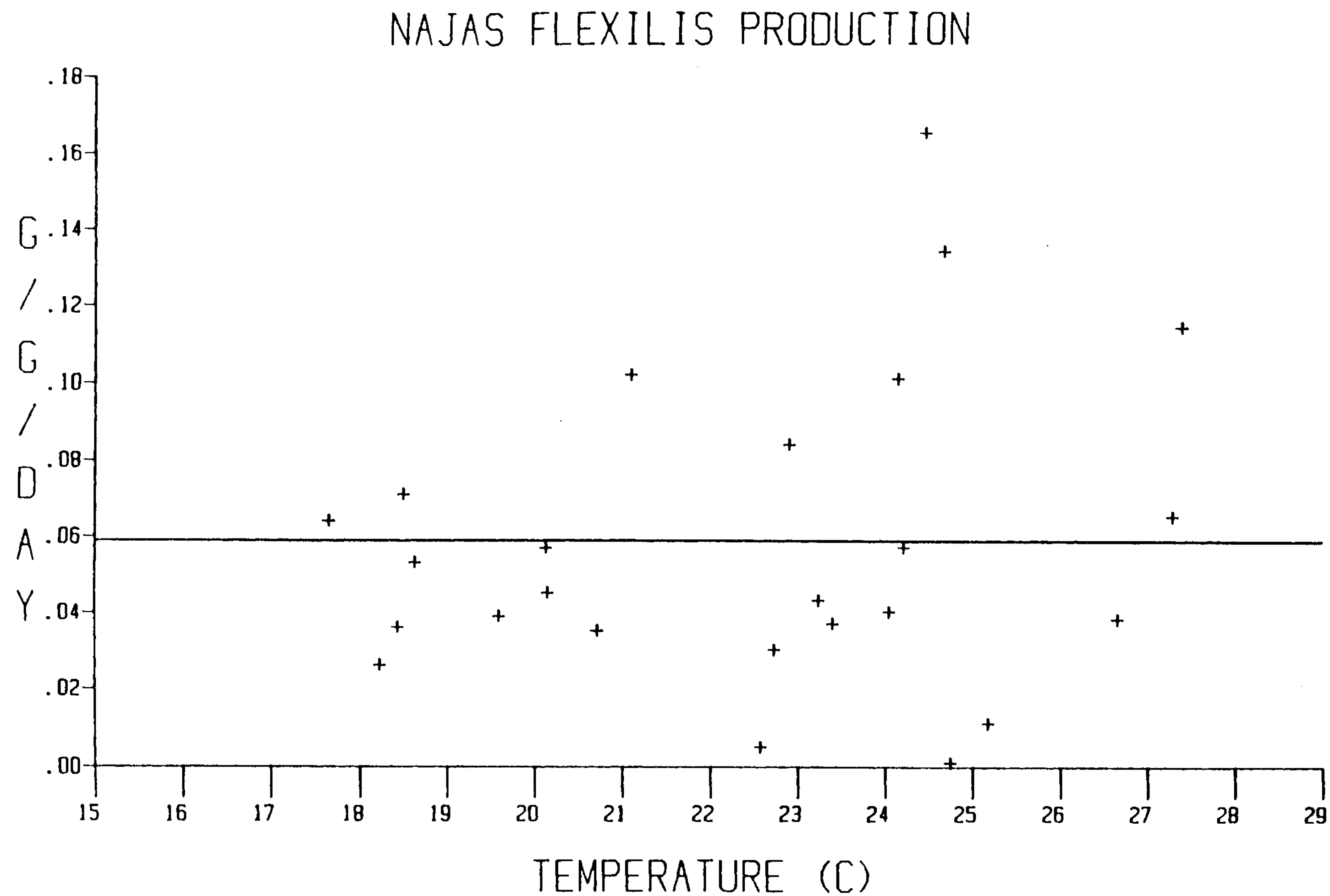


Fig. 3-9. Observed (points) and modelled (line) _Najas flexilis_ production (g/g * day) as a function of pond temperature (°C).

The instantaneous mortality coefficient is modelled as a power function of annual cumulative degree-days (above 0°C), providing a seasonally accelerating mortality which eventually overcomes growth and results in a natural die-back of the plant population. The parameters a and b in Eq. 17 were estimated from field data by simple least squares for each species with no overwintering shoot biomass except *Myriophyllum* spp. (Figs. 3-10 through 3-13).

Potamogeton crispus is a perennial species that overwinters in the third or fourth cohort, and it required a different functional relationship to model its natural mortality cycle. Like an annual, *P. crispus* goes through a seasonal die-back; in its case this usually occurs in the early or middle summer (Wiley et al. 1983). Unlike an annual, rhizomes and turions give rise to a new cohort in the late summer which grows into the fall, overwinters, and completes development the following spring. This results in a bimodal biomass phenology and a mortality pattern that we have modelled using a simple sine function:

$$M = a + b * \sin(DEGDAY) \qquad (18)$$

This function generates the required bimodal phenology and can be fitted to field data by least squares methods (Fig. 3-14). The combination of Eqs. 17 and 18 results in acceptably realistic seasonal biomass phenologies. Because the mortality rates are controlled by cumulative degree-days, the model has the additional property of being able to adjust the plant phenologies to variations in annual temperature cycles. Thus as input temperatures are raised, seasonal growth and mortality occur earlier in the year; if temperatures are lowered they occur later. Peak biomass varies minimally with these temperature-induced alterations in phenology. The one perennial with overwintering shoots we modelled, *P. crispus*, is an exception in that changes in temperature cycles cause overwintering biomass to vary substantially, often resulting in destabilizing growth or mortality. As a result, simulations with this species have been restricted to Region 11 (see below), the region from which all data used to estimate rate coefficients were collected.

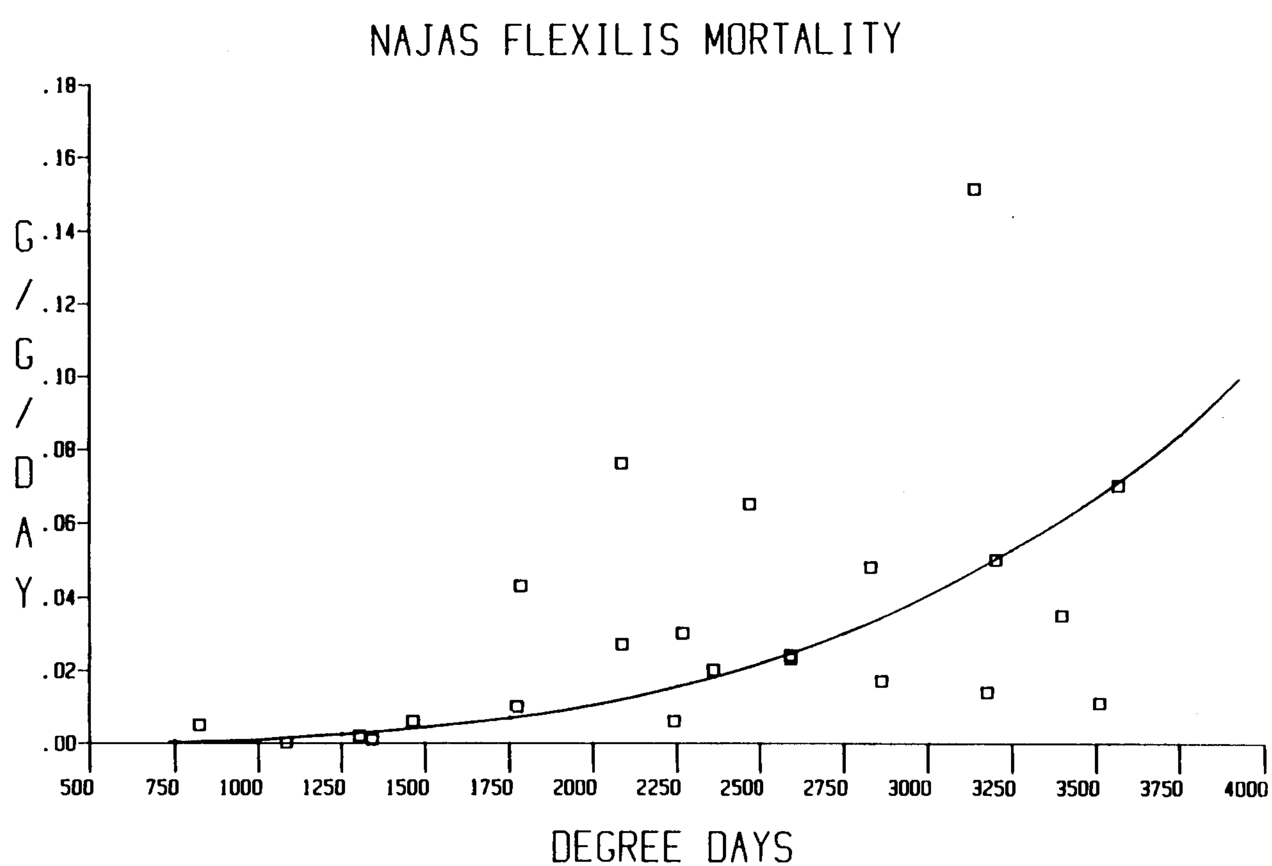


Fig. 3-10. Observed (points) and modelled (line) mortality rate (g/g * day) of *Najas flexilis* as a function of cumulative degree days.

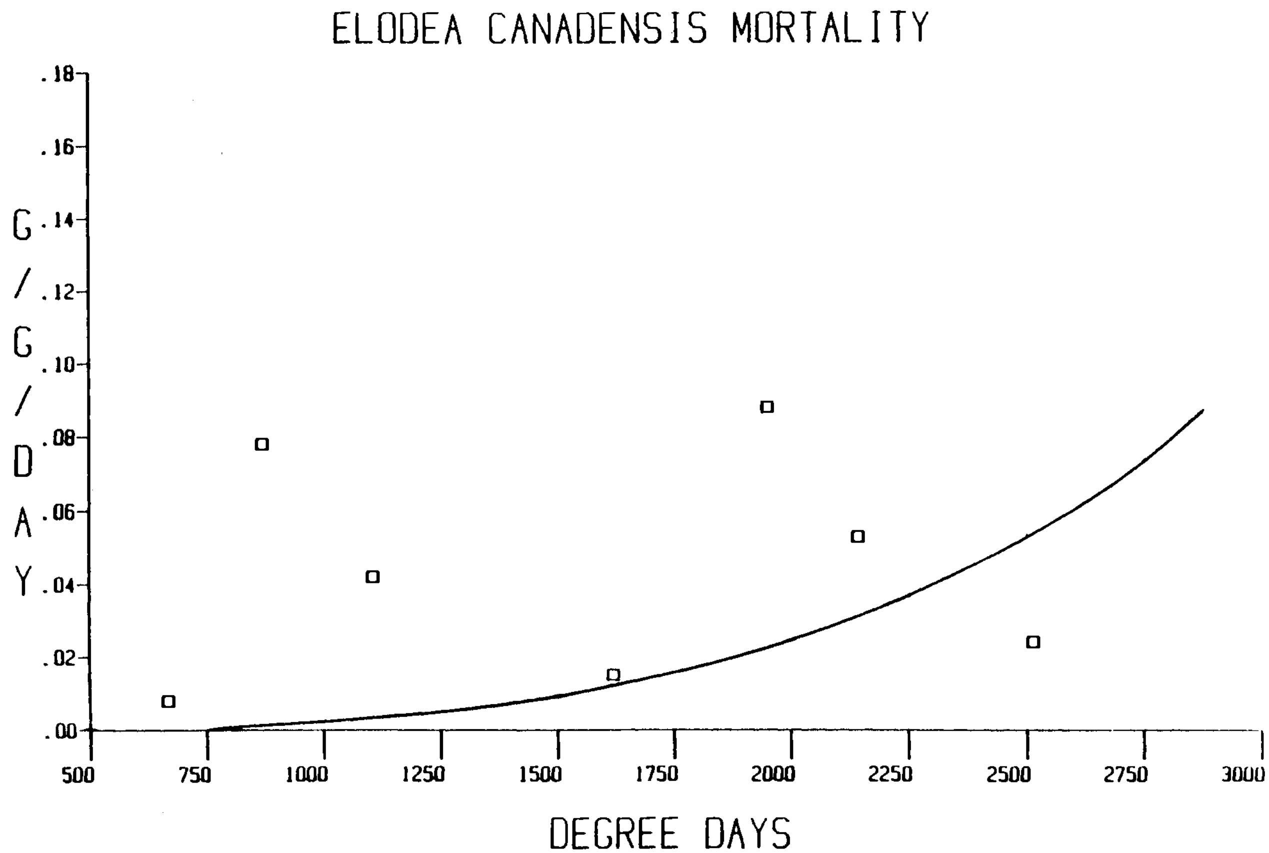


Fig. 3-11. Observed (points) and modelled (line) mortality rate (g/g * day) of *Elodea canadensis* as a function of cumulative degree days.

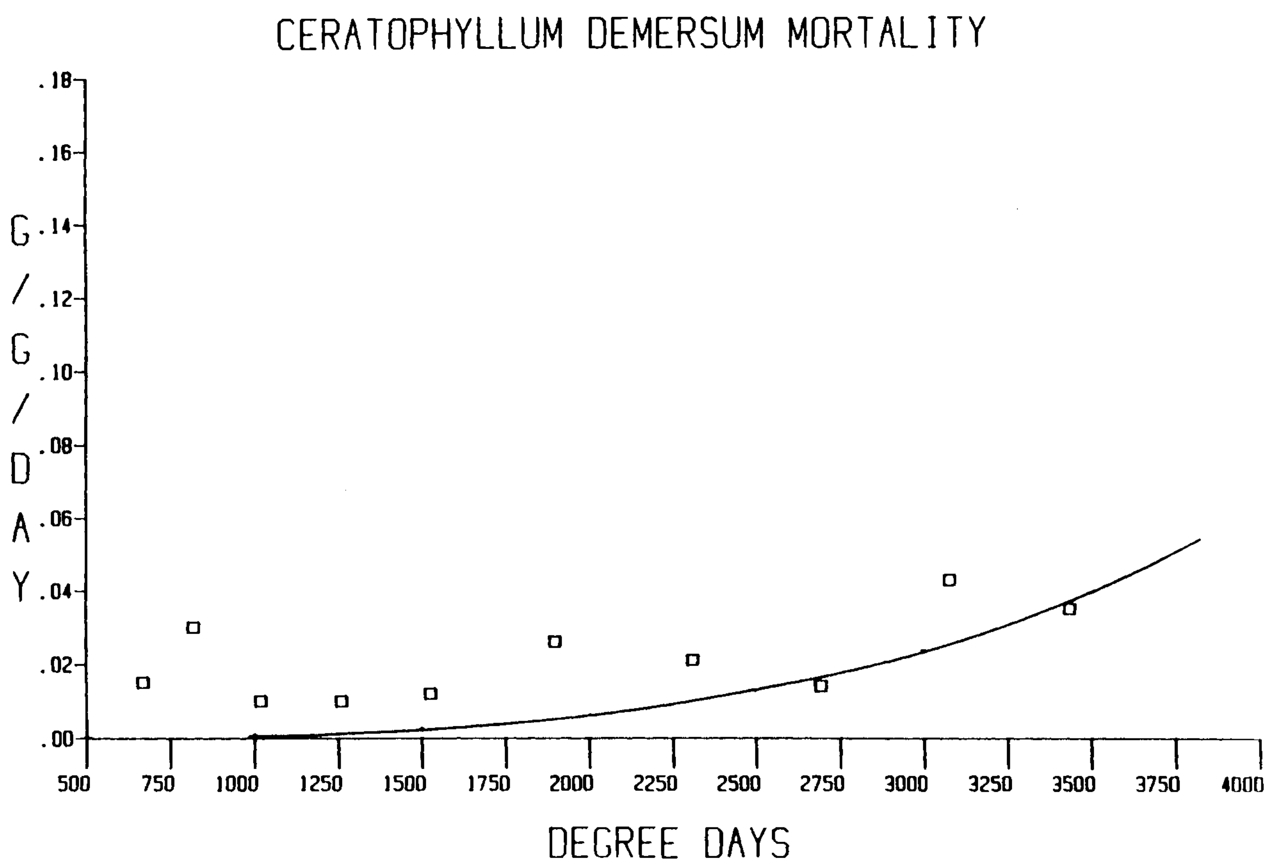


Fig. 3-12. Observed (points) and modelled (line) mortality rate (g/g * day) of *Ceratophyllum demersum* as a function of cumulative degree days.

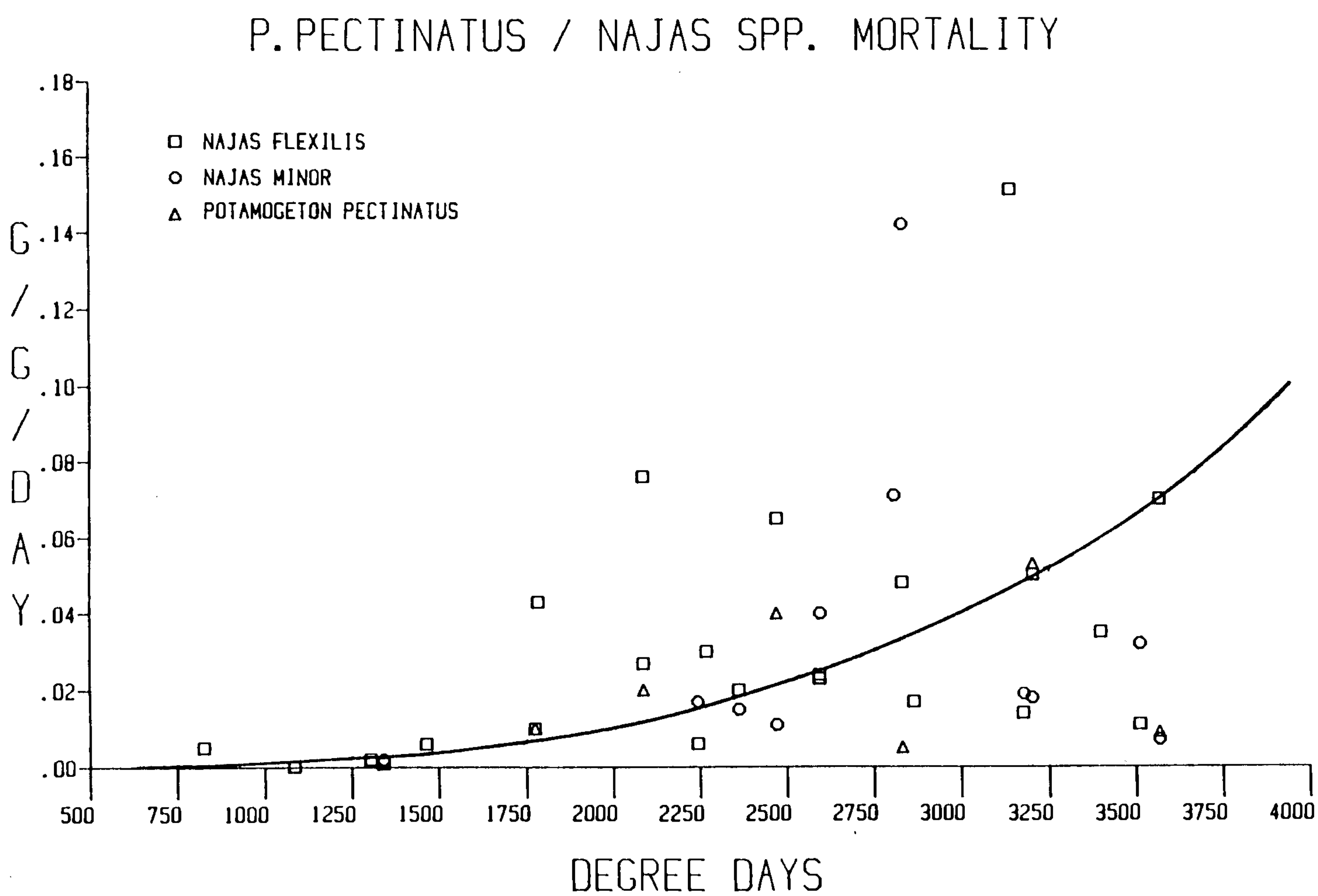


Fig. 3-13. Mortality rate (g/g * day) of <u>Potamogeton pectinatus/Najas</u> spp. as a function of cumulative degree days.

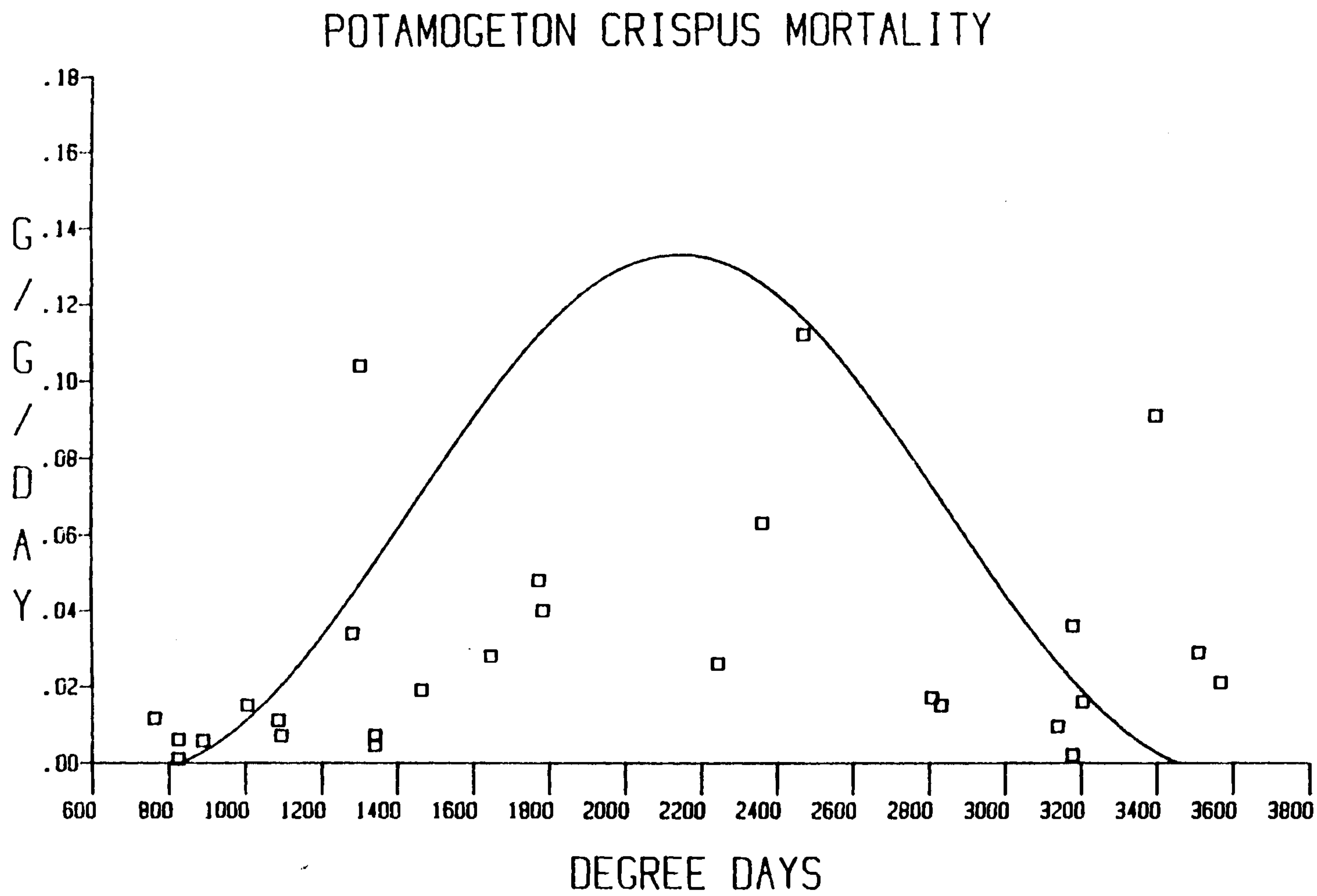


Fig. 3-14. Observed (points) and modelled (line) mortality rate (g/g * day) of _Potamogeton crispus_ as a function of cumulative degree days.

Grazing mortality (units = g/m^2 * day) are estimated by the carp bioenergetic submodel as described above (see Eq. 2). A biomass reserve of 5 g dry weight/m^2 was made inaccessible to the carp and other mortality sources to prevent the plant compartments from reaching a stable equilibrium of zero. Conceptually, this reserve represents dispersed and/or undergrazed reproductive tissues, such as seeds, turions, and rhizomes.

4. REGIONAL TEMPERATURE DATA BASE

Both the bioenergetic submodel and the plant production submodel require daily water temperature as a driving variable. These data are derived from the 30-year daily mean temperature records published for 20 climatic regions in Illinois by the Illinois State Water Survey. Weekly mean air temperatures for a particular region are loaded from disk prior to a simulation. Epilimnetic temperatures are estimated from these air temperatures during simulation using:

$$\text{Water temperature (°C)} = 3.06 + 0.931 * \text{air temperature (°C)} \qquad (19)$$

This relationship was derived from a statistical analysis of temperature data from the INHS pond site collected from 1982 through 1984 (Fig. 3-15) and provides a general predictor of water temperature at a depth of a meter or less. Obviously each body of water has its own peculiar thermal characteristics; if weekly temperature data are available, they can and should be substituted for the regional files.

MODEL IMPLEMENTATION

The IHF3S program is coded in FORTH, an extensibile, threaded, interpreted language and is implemented on an Apple IIe microcomputer. A listing of the source code for major system components is given in Appendix 3. The version of FORTH used is a commercial product of Applied Analytics Inc. (Marlboro, MD) marketed under the name Microspeed™. Microspeed FORTH is an

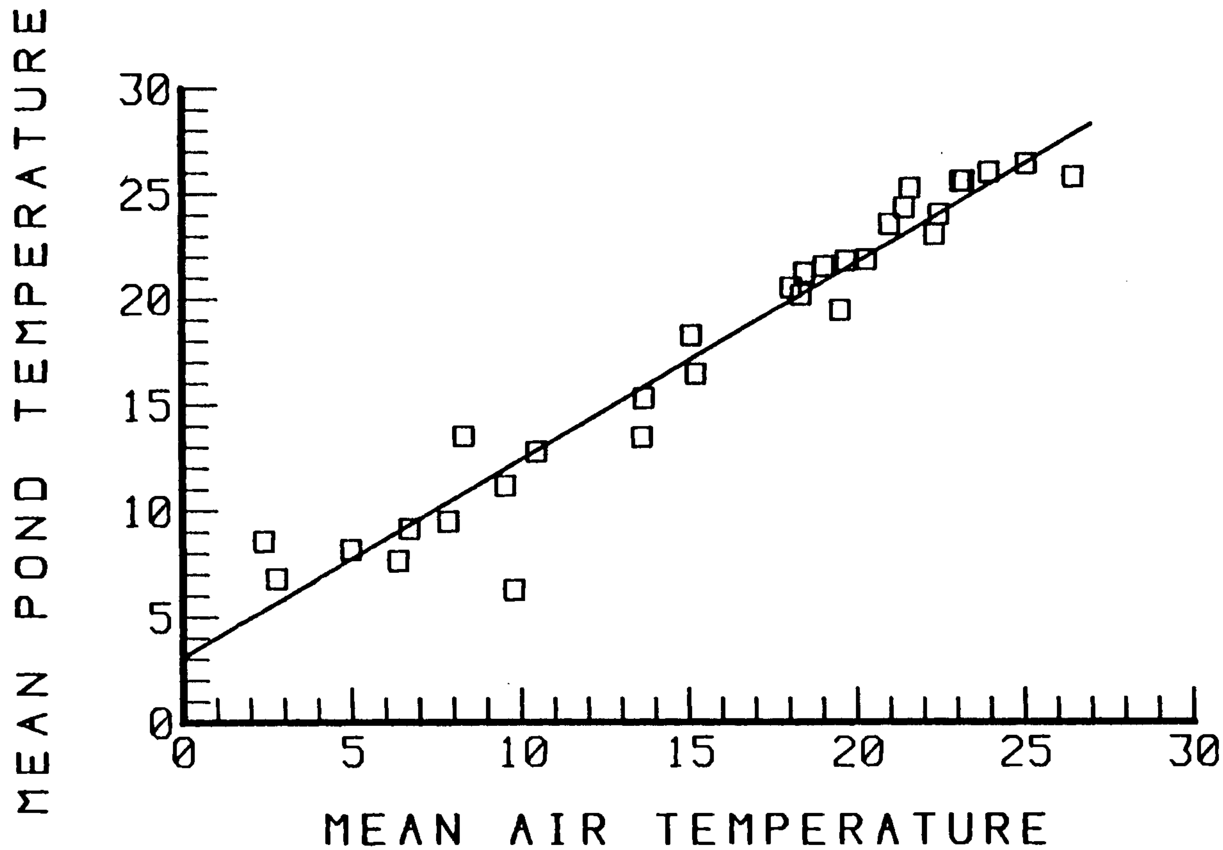


Fig. 3-15. Correlation of average weekly mean pond and air temperatures (°C) for INHS experimental ponds. Regression equation is $Y = 0.931X + 3.066$, $r^2 = 0.94$.

extension of Fig-FORTH optimized for the Apple's 6502 proceessor, DOS 3.3, and for hardware floating-point operations via an INTEL 8231A co-processor. Support of floating-point hardware was the key determinant in our choice of Applied Analytics' FORTH, because the model is computationally intensive and runs slowly without the assistance of one or more co-processor boards. However, FORTH is relatively portable and the source code would require only minor alterations to be used with standard FORTH-79 or FORTH-83 compilers on the Apple or any other hardware system. The hardware configuration used in the simulations reported here consisted of an Apple IIe computer with 128-K RAM, a 3.5-MHz 6502C co-processor board (Titan Inc.), a 4-MHz INTEL 8231A floating-point co-processor board (Applied Analytics Inc., Marlboro, MD), two disk drives, a dot-matrix printer, and a Hewlett-Packard 7470a plotter.

USER INTERFACE

The User Interface is a collection of subroutines that control model execution, option selection, and input/output functions. It is a highly flexible command driven interface so that a user can examine the effects of almost any stocking strategy imaginable. Commands can be issued from the keyboard at any time and in any order (assuming correct syntax). Available commands can be grouped into three categories:

(1) Initialization Commands. These routines define the basic characteristics of the current simulation; for example, they can be used to control the ploidy of the carp, the species of plant, the climatic region, etc.

(2) Execution Commands. These routines are used directly to start, stop, and restart individual simulations.

(3) Input/Output Commands. These routines are used to modify model parameters, view variable values, and select types of model output.

While no attempt will be made in this report to provide an exhaustive description of how to use IHF3S, a short Command Glossary is provided. This glossary contains a listing and description of most key system commands and can serve as a basic introduction to using the models decribed here.

COMMAND GLOSSARY

COMMAND SYNTAX

IHF3S is written in FORTH and as such retains for the most part a typical FORTH-like syntax. Commands with numerical arguments generally require the argument to be entered before the command:

e.g., < arg > < command >

On the other hand, commands with text argument (typically names) generally require the argument to follow the command:

e.g., < command > < arg >

Some commands in IHF3S require no arguments at all: e.g., < command >

In any case, commands may be entered one per line, followed by a carriage return ([CR]); or they may be entered sequentially on one or more lines (up to 255 characters) terminated by a carriage return. Comands may also be compiled into the FORTH dictionary (similar to a command macro) using standard FORTH definition words.

1. Initialization Commands

READTEMP syn READTEMP < FILENAME > [CR]; loads temperature data from file containing weekly mean air temperatures. IHF3S contains 20 regional climate files named by region; e.g., REGION11 , REGION1. System boots up with REGION11 loaded. User may substitute any DOS 3.3 text file.

SETPLANTS syn SETPLANTS < arg > [CR]; sets up model to run with plant species designated by < arg >. Plants currently available and their corresponding arguments are:

1. *Myriophyllum* spp.; < arg > = MYRIOPHYLLUM
2. *Ceratophyllum demersum*; < arg > = CERATOPHYLLUM
3. *Elodea canadensis*; < arg > = ELODEA
4. *Potamogeton pectinatus*/*Najas* spp.; < arg > = SAGO/NAJAS
5. *P. crispus*/*Najas flexilis*; < arg > = CRISPUS/NAJAS

TRIPLOID syn TRIPLOID [CR]; sets model to run simulations for triploid grass carp.

DIPLOID syn DIPLOID [CR]; sets model to run simulations for diploid grass carp.

2. Execution Commands

SETUP syn SETUP [CR]; begins interactive session in which user is prompted for stocking information; used to setup for a simulation run.

RUN syn RUN [CR]; begins or continues a simulation using all currently defined values. RUN does not reset any values; use RESET to initialize model to time zero and values established by SETUP.

RESET syn RESET [CR]; resets model to day and year zero and uses SETUP information to prepare a stocking sequence. To begin a run of the model use the following sequence of commands SETUP RESET GINIT RUN [CR].

GINIT syn GINIT [CR]; initialize graphics display for a simulation using current axes definitions.

DUMPG syn DUMPG [CR]; directs the graphics display on the monitor to be sent to the printer. Graphic output from a simulation can be displayed on the monitoring using GINIT or GRAPH.

DUMPS syn DUMPS [CR]; directs text or tabular output on the monitor screen to be sent to the printer.

3. Input/Output Commands

PRINTER_ON syn PRINTER_ON [CR]; directs table output to the printer in slot 1 during simulation.

PRINTER_OFF syn PRINTER_OFF [CR]; stops printer output.

PLOTINIT syn PLOTINIT [CR]; initializes plotter. Must be used prior to PLOTTER_ON. Can also be used to recover from plotter error condition.

PLOTTER_ON syn PLOTTER_ON [CR]; all subsequent graphical output is duplicated on both the screen and on the system plotter.

PLOTTER_OFF syn PLOTTER_OFF [CR]; all subsequent graphical output is sent only to the monitor.

GRAPH syn GRAPH [CR]; instructs monitor to display graphics page.

TEXT syn TEXT [CR]; instructs monitor to display text page.

CLEAR syn CLEAR [CR]; clears graphics display to black.

=PLOT syn < arg > =PLOT [CR]; the variable named in argument will be plotted during the next simulation run; e.g., PLANT1 =PLOT [CR].

SEE syn < arg > SEE [CR]; the current value of the floating-point variable named in the argument will be printed to the current output device.

SET syn < arg > SET < value > [CR]; sets the floating-point variable in argument to the value specified.

? syn < arg > ? [CR]; the current value of the integer variable named in the argument is printed.

! syn < val > < arg > ! [CR]; sets integer variable in argument to value specified.

FLTITL syn FLTITL [CR] < position with I, J, K, M keys > [CR]; moves label cursor under keyboard control in preparation for adding a label to a output graph.

" (") syn "< label >" [CR]; defines a floating label to be placed on a graphic output.

LABEL syn "< label >" LABEL [CR]; writes preceeding label at current label coordinates.
Example usage: FLTITL [CR] "label1" LABEL [CR]

<u>Some Key System Variables</u>

XMAX, YMAX Floating point variables holding maximum values for x and y axes; use "SET" to change values.

XTICS, YTICS Integer variables holding the number of tic marks per axis; change using < val > XTICS !

#YEAR	Floating-point variable holding the number of years the simulation will run; note #YEAR = XMAX in most cases.
MPEAK	Floating-point variable holding the annual peak plant biomass. MPEAK is determined by simulation of plant growth without fish. It is set automatically for simulations in Region 11. For simulations run in other regions or using user-supplied temperature data, MPEAK should be set by hand after the appropriate simulation (e.g., MPEAK set < val >
PLANT1	Floating-point variable holding the current biomass (g dry weight/m^2) of the simulated macrophyte population with overwintering shoots.
PLANT2	Floating-point variable holding the biomass (g dry weight/m^2) of simulated annual species and perennial species with overwintering reproductive structures only.
PTOTAL	Floating-point variable holding the total biomass (g dry weight/m^2) of macrophytes.
SIZE1, SIZE2, SIZE3	Floating-point variable holding the current size (g fresh weight) of carp in stocking groups 1 through 3.
FNUM1, FNUM2, FNUM3	Floating-point variable holding the current number of fish in stocking groups 1 through 3.

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Appendix 1.

FOUR-YEAR BATCH STOCKING CURVES

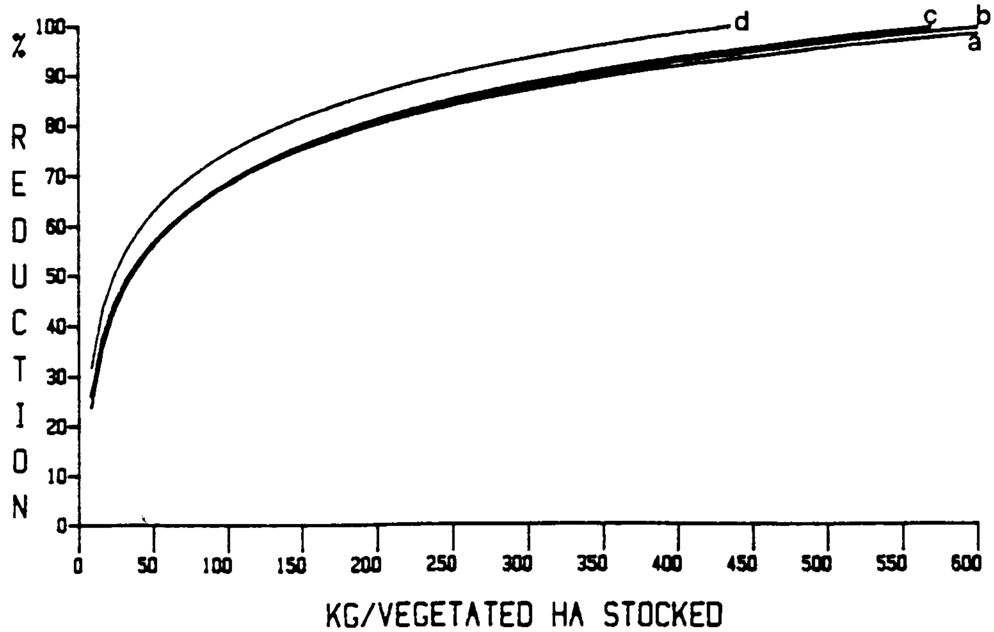


Fig. A1-1. Stocking curves for Potamogeton pectinatus/ Najas spp. in Region 11 using 4-year batch stocking strategy. Simulations included four sizes of triploid grass carp: a = 50 g, b = 100 g, c = 200 g, and d = 400 g.

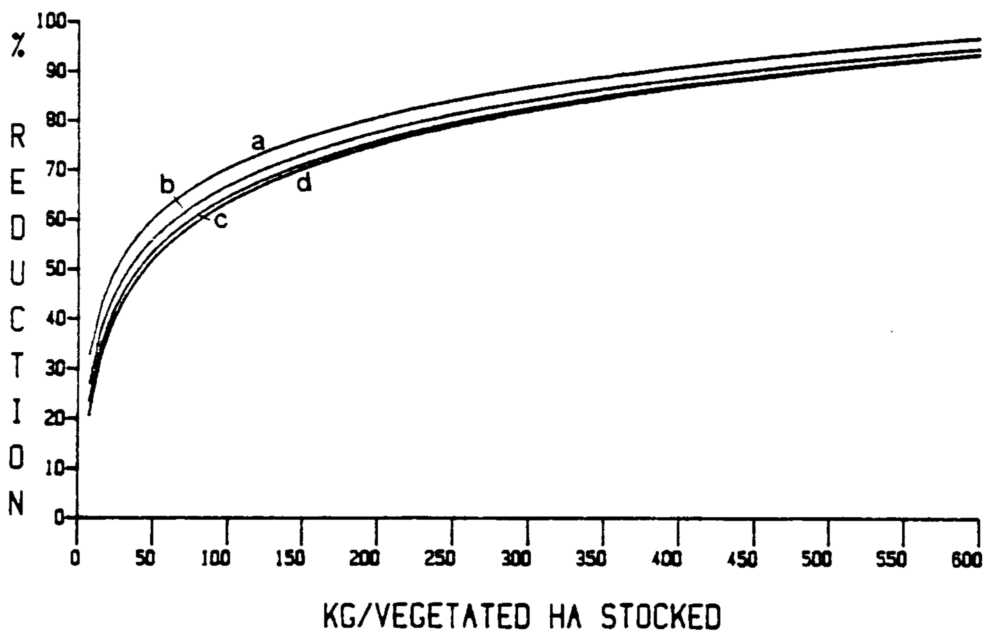


Fig. A1-2. Stocking curves for Elodea canadensis in Region 11 using 4-year batch stocking strategy. Simulations included four sizes of triploid grass carp: a = 50 g, b = 100 g, c = 200 g, and d = 400 g.

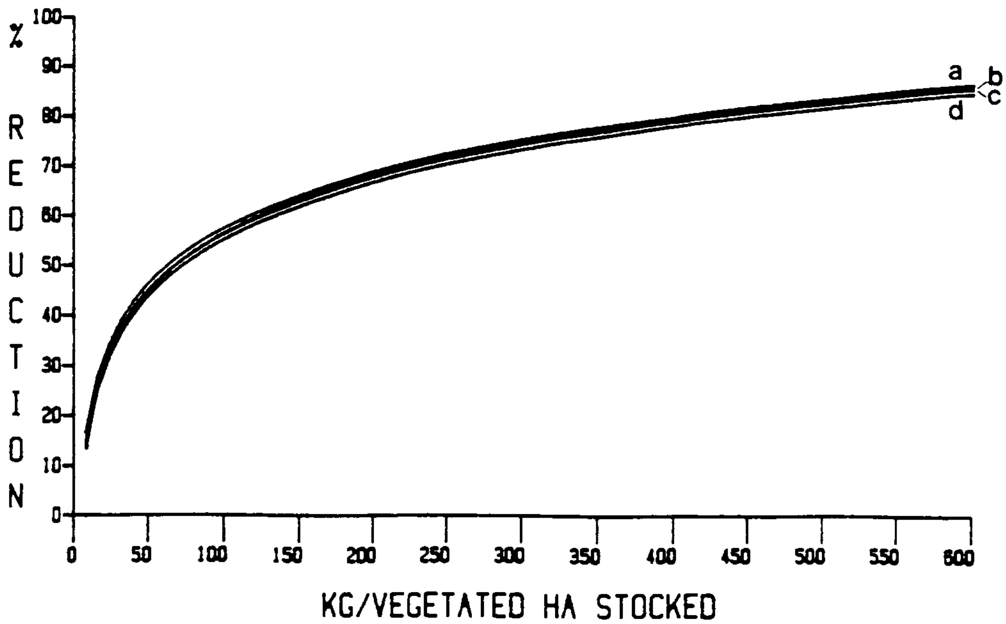


Fig. A1-3. Stocking curves for <u>Ceratophyllum demersum</u> in Region 11 using 4-year batch stocking strategy. Simulations included four sizes of triploid grass carp: a = 50 g, b = 100 g, c = 200 g, and d = 400 g.

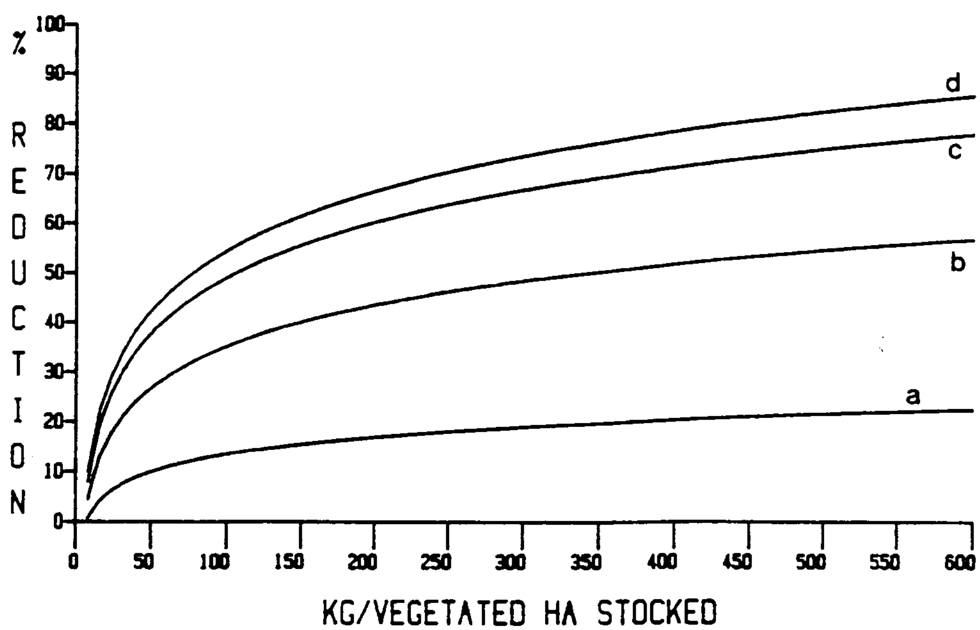


Fig. 1-4. Stocking curves for <u>Myriophyllum</u> spp. in Region 11 using 4-year batch stocking strategy. Simulations included four sizes of triploid grass carp: a = 50 g, b = 100 g, c = 200 g, and d = 400 g.

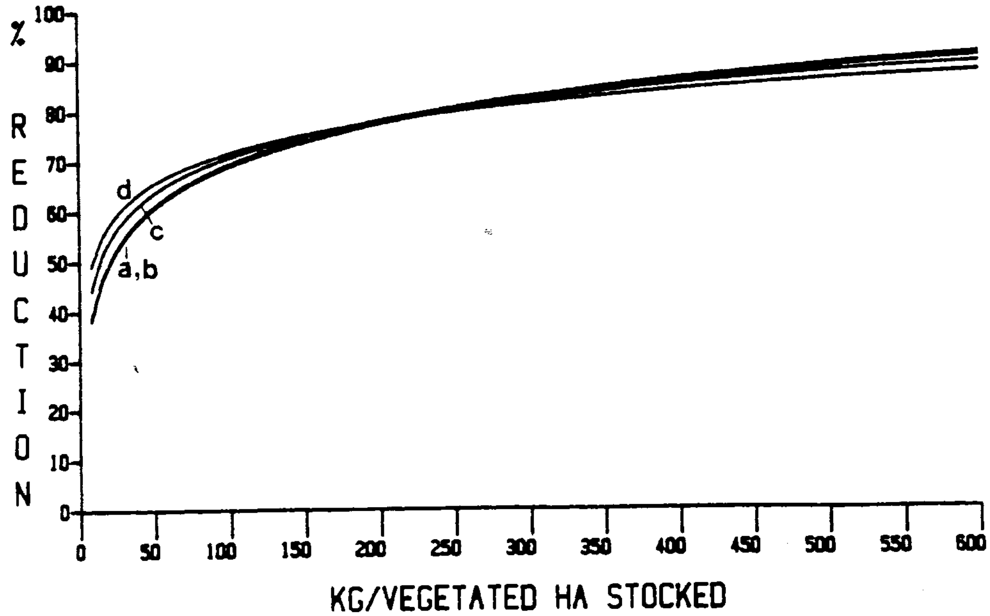


Fig. A1-5. Stocking curves for Potamogeton crispus/ Najas flexilis in Region 11 using 4-year batch stocking strategy. Simulations included four sizes of triploid grass carp: a = 50 g, b = 100 g, c = 200 g, and d = 400 g.

Appendix 2

IHF3S SIMULATIONS USING A SERIAL STOCKING STRATEGY IN REGIONS 1, 6, 11, 15, AND 19

Simulated levels (g dry weight m^{-2}) of all five macrophyte assemblages are presented for both the best management practice (BMP) and eradication scenarios.

Fig. A2-1. BMP control of <u>Potamogeton pectinatus</u>/<u>Najas</u> spp. in Region 1.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	5	2373	0	0	0	0	160949.9	160949.9
2	5	5046	0	0	0	0	134944.7	147947.3
3	4	8093	0	0	0	0	74898.18	123597.6
4	3	14456	0	0	0	0	21478.57	98067.85
5	3	14345	0	0	0	0	74988.11	93451.89
6	3	14465	5	1974	0	0	27889.05	82524.73
7	2	14248	4	3807	0	0	70264.34	80773.26
8	1	14145	3	6459	0	0	47109.32	76565.27
9	1	14342	2	11902	0	0	21954.24	70497.36
10	1	14252	2	14478	0	0	17393.38	65186.97

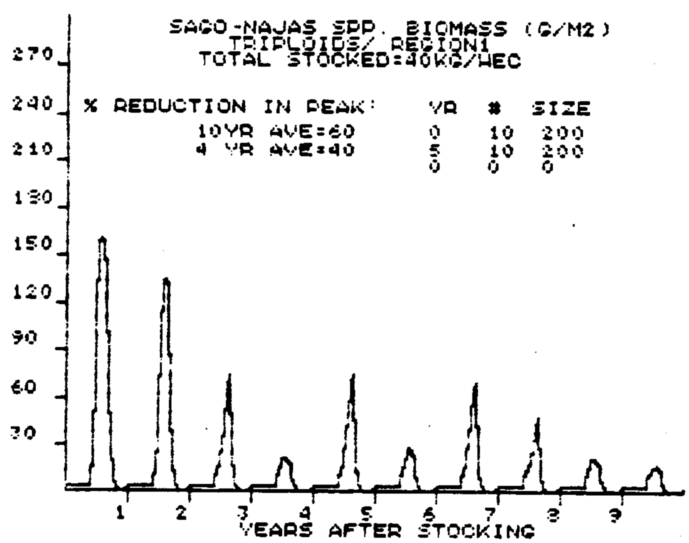


Fig. A2-2. Eradication of Potamogeton pectinatus/Najas spp. in Region 1.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	29	1946	0	0	0	0	145475.0	145475.0
2	21	4442	0	0	0	0	21570.66	83522.84
3	14	7643	0	0	0	0	21658.35	62901.33
4	9	12270	0	0	0	0	21604.30	52577.08
5	7	16778	0	0	0	0	21661.85	46394.04
6	5	19625	0	0	0	0	21642.38	42268.76
7	3	22097	0	0	0	0	21478.57	39298.72
8	2	19423	15	1360	0	0	31100.52	38273.95
9	1	16027	11	2488	0	0	17607.85	35977.71
10	1	14367	8	5376	0	0	23726.41	34752.58

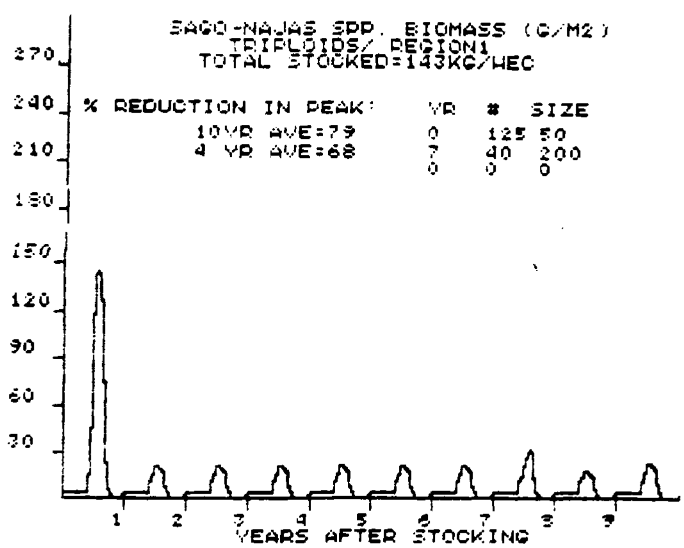


Fig. A2-3. BMP control of Potamogeton pectinatus/Najas spp. in Region 6.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	6	3373	0	0	0	0	158545.7	158545.7
2	5	7342	0	0	0	0	94525.68	126535.7
3	4	15538	0	0	0	0	24876.82	92649.41
4	3	14528	0	0	0	0	73144.33	87773.14
5	3	14491	0	0	0	0	78067.13	85831.92
6	2	14931	4	2172	0	0	23293.68	75408.89
7	2	14424	3	5104	0	0	75528.75	75426.02
8	1	14213	3	7892	0	0	85219.14	76650.16
9	1	14268	2	11966	0	0	29911.21	71456.93
10	1	14134	2	15503	0	0	20436.94	66354.93

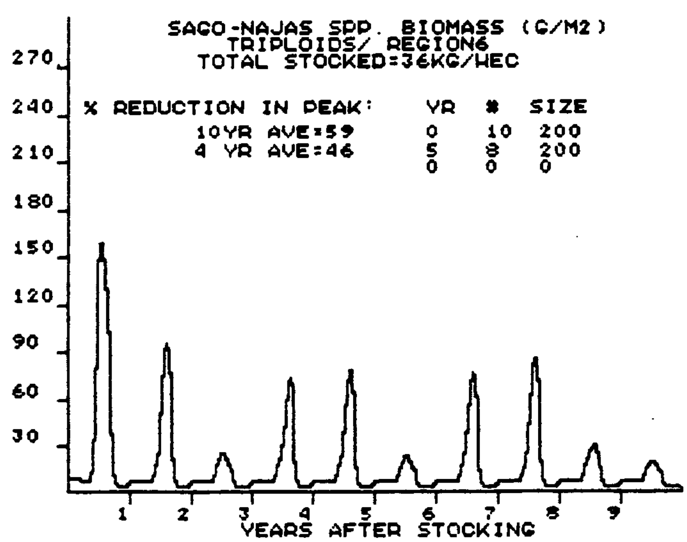


Fig. A2-4. Eradication of <u>Potamogeton pectinatus</u>/<u>Najas</u> spp. in Region 6.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	27	2751	0	0	0	0	140995.2	140995.2
2	18	5472	0	0	0	0	24756.09	82875.66
3	11	9452	0	0	0	0	24745.75	63499.03
4	7	15307	0	0	0	0	24864.29	53840.34
5	5	19955	0	0	0	0	24657.27	48003.73
6	3	25107	0	0	0	0	24676.75	44115.89
7	2	13809	9	396	0	0	22742.50	41062.55
8	1	13809	3	416	0	0	22725.66	38770.44
9	0	13809	3	3588	5	2200	17752.18	36435.07
10	0	13809	2	7862	4	4723	23136.33	35105.19

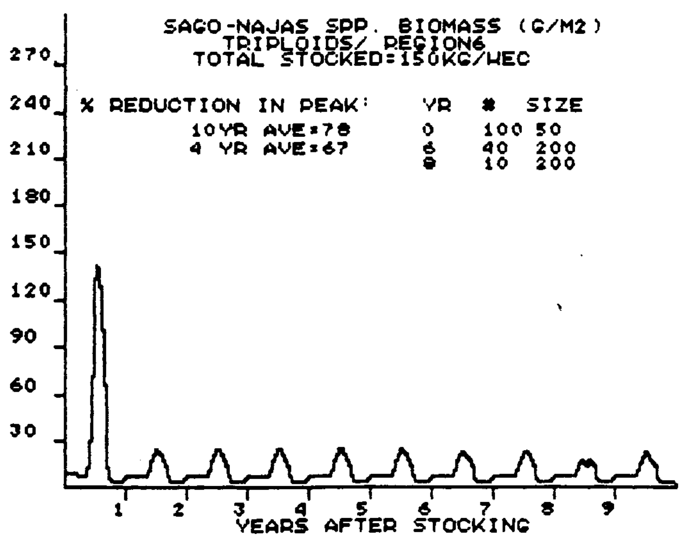


Fig. A2-5. BMP control of <u>Potamogeton pectinatus</u>/<u>Najas</u> spp. in Region 11.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	6	3399	0	0	0	0	154421.7	154421.7
2	5	7379	0	0	0	0	89891.63	122156.7
3	4	16104	0	0	0	0	21253.89	88522.40
4	3	14504	0	0	0	0	72307.82	84468.76
5	3	14442	0	0	0	0	70639.59	81702.92
6	2	15151	3	2026	0	0	19764.32	71379.83
7	2	14356	3	5063	0	0	73185.80	71637.84
8	1	14039	2	7810	0	0	101273.8	75342.33
9	1	14234	2	13569	0	0	22220.23	69439.85
10	1	14205	1	14954	0	0	16482.79	64144.15

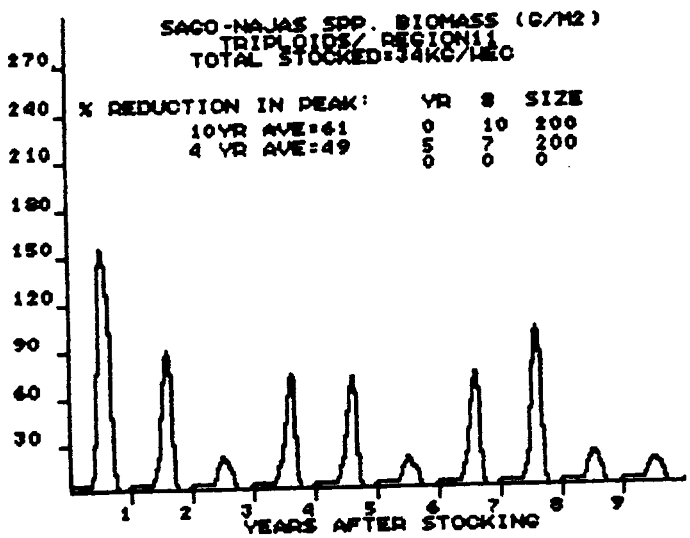


Fig. A2-6. Eradication of Potamogeton pectinatus/Najas spp. in Region 11.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	26	2841	0	0	0	0	138359.8	138359.8
2	17	5679	0	0	0	0	21132.88	79746.37
3	11	9821	0	0	0	0	21206.20	60232.97
4	7	15765	0	0	0	0	21196.27	50473.80
5	5	20503	0	0	0	0	21165.87	44612.22
6	3	26532	0	0	0	0	21039.55	40683.44
7	2	13523	6	407	0	0	18456.90	37508.22
8	1	13523	1	710	0	0	19923.18	35310.09
9	0	13523	1	4221	9	2777	15689.53	33130.02
10	0	13523	1	7340	7	7964	22267.04	32043.72

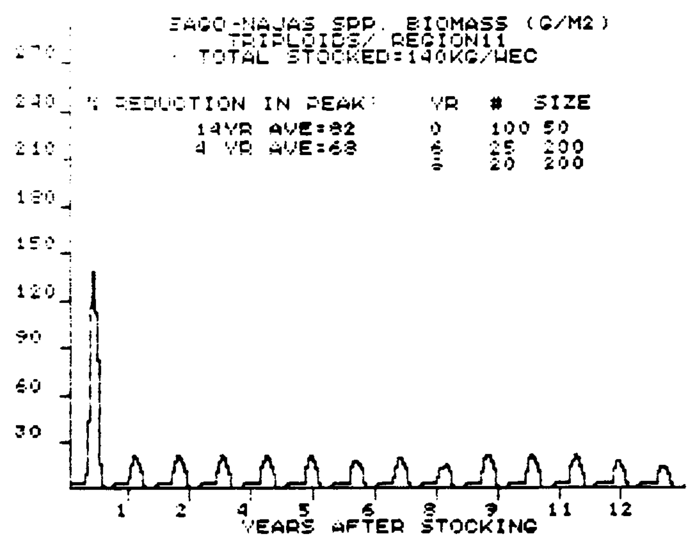


Fig. A2-7. BMP control of Potamogeton pectinatus/Najas spp. in Region 15.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	9	4144	0	0	0	0	145562.2	145562.2
2	6	11226	0	0	0	0	23921.81	84742.02
3	4	17338	0	0	0	0	24035.44	64506.49
4	3	14589	0	0	0	0	36268.15	57446.90
5	3	14118	0	0	0	0	57483.37	57454.19
6	2	14228	3	3016	0	0	98512.74	64297.28
7	1	14618	2	7082	0	0	32113.75	59699.63
8	1	14122	2	10293	0	0	63114.37	60126.47
9	1	14224	1	14386	0	0	22304.87	55924.07
10	0	15008	1	14001	0	0	113517.7	61683.44

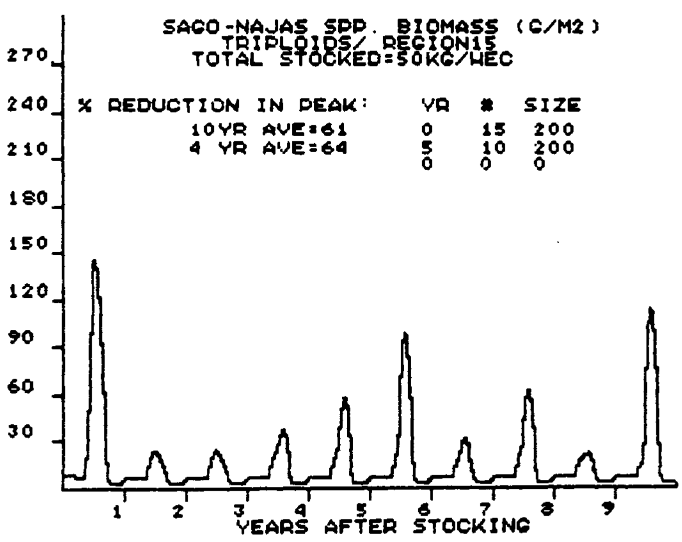


Fig. A2-8. Eradication of _Potamogeton pectinatus_/_Najas_ spp. in Region 15.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	35	2974	0	0	0	0	113321.6	113321.6
2	19	4377	0	0	0	0	23913.18	68617.40
3	10	7560	0	0	0	0	23892.75	53709.17
4	6	13832	0	0	0	0	23901.78	46257.32
5	4	19111	0	0	0	0	23784.72	41762.80
6	2	21560	0	0	0	0	23782.33	38766.05
7	2	18931	11	1394	0	0	32143.24	37819.93
8	1	14423	8	4536	2	638	31576.81	37039.54
9	1	14345	4	7401	1	429	22185.26	35389.06
10	0	16345	2	12534	0	482	18018.62	33652.02

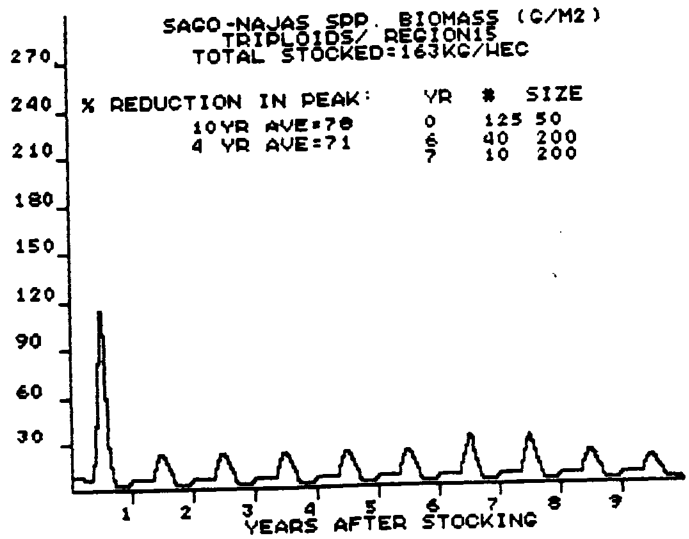


Fig. A2-9. BMP control of <u>Potamogeton pectinatus</u>/<u>Najas</u> spp. in Region 19.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	6	5304	0	0	0	0	145951.2	145951.2
2	4	13828	0	0	0	0	20351.78	83151.53
3	3	14393	0	0	0	0	50451.29	72251.44
4	3	14353	0	0	0	0	46245.68	65749.99
5	2	14236	4	4032	0	0	61957.64	64991.53
6	2	15028	2	5901	0	0	21523.89	57746.91
7	1	14320	1	12431	0	0	17967.95	52064.20
8	1	14079	1	14064	0	0	58550.13	52874.94
9	1	14005	1	14100	0	0	56492.27	53276.86
10	0	13654	1	14156	0	0	116673.6	59616.54

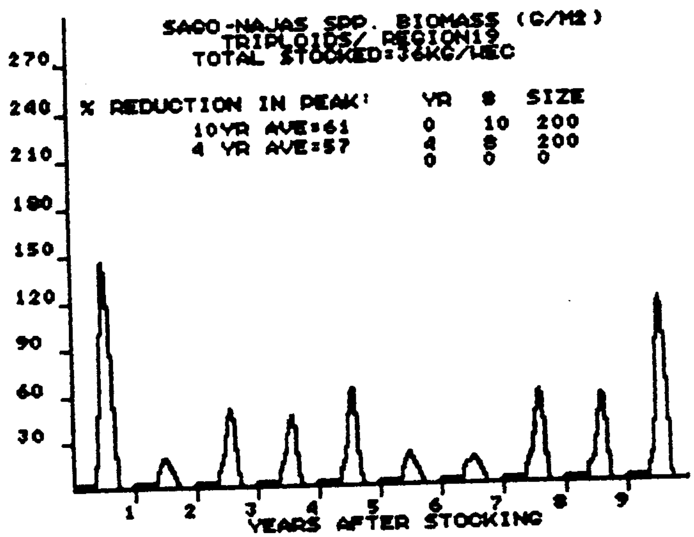


Fig. A2-10. Eradication of Potamogeton pectinatus/Najas spp. in Region 19.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	23	3399	0	0	0	0	125731.2	125731.2
2	13	5399	0	0	0	0	20341.07	73036.17
3	7	9416	0	0	0	0	20317.37	55463.23
4	4	15802	0	0	0	0	20263.87	46663.39
5	3	19666	0	0	0	0	20208.90	41372.49
6	2	17580	9	1067	0	0	25153.18	38669.27
7	1	16114	5	2110	0	0	18294.10	35758.53
8	1	14442	4	5425	6	864	30426.93	35092.08
9	1	14723	2	10218	2	257	16198.03	32992.74
10	0	14622	2	14714	0	2453	25837.84	32277.25

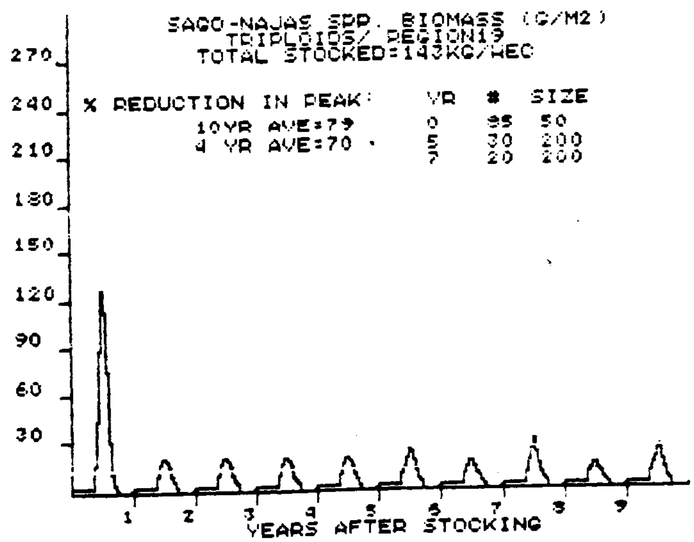


Fig. A2-11. BMP control of <u>Elodea canadensis</u> in Region 1.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	11	2380	0	0	0	0	413333.5	413333.5
2	10	5675	0	0	0	0	331366.2	372349.9
3	9	12750	0	0	0	0	50488.49	265062.7
4	7	14459	0	0	0	0	101070.7	224064.8
5	7	14465	6	1714	0	0	135001.7	206252.1
6	6	14407	5	3635	0	0	155230.5	197748.5
7	5	14335	4	5787	0	0	171507.0	193999.7
8	3	14376	4	8253	0	0	85118.70	180389.6
9	2	14182	3	10949	0	0	90845.02	170440.1
10	1	14141	3	12941	0	0	126588.1	166055.0

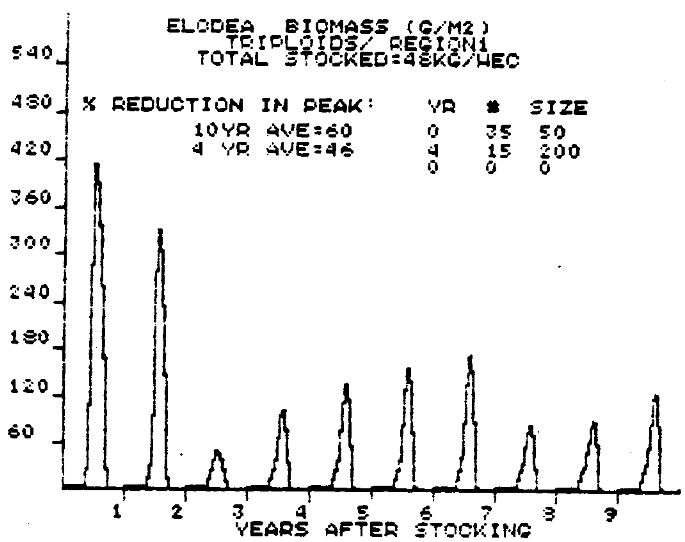


Fig. A2-12. Eradication of Elodea canadensis in Region 1.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	30	2362	0	0	0	0	400344.8	400344.8
2	23	7060	0	0	0	0	50493.31	225419.1
3	16	13695	0	0	0	0	50736.86	167191.6
4	12	18358	0	0	0	0	50639.76	138053.7
5	9	23118	0	0	0	0	50510.23	120544.9
6	7	28965	0	0	0	0	50422.94	108857.9
7	4	13301	6	457	0	0	47836.44	100140.6
8	2	13301	3	830	0	0	47676.05	93582.53
9	1	13301	0	1078	0	0	47583.71	88471.55
10	0	13301	0	1078	12	2804	41054.32	83729.81

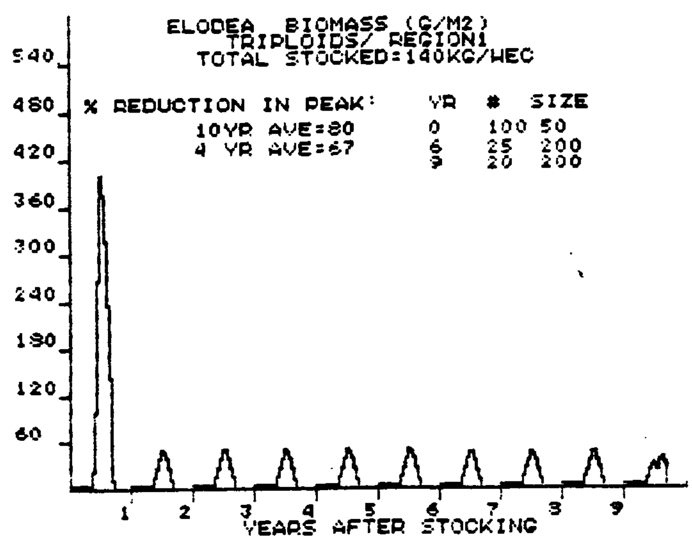


Fig. A2-13. BMP control of <u>Elodea canadensis</u> in Region 6.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	11	3304	0	0	0	0	409883.9	409883.9
2	10	8077	0	0	0	0	227855.0	318869.4
3	8	15772	0	0	0	0	52540.40	230093.1
4	7	14344	0	0	0	0	136685.0	206741.0
5	6	14262	0	0	0	0	213408.8	208074.6
6	5	14504	8	2780	0	0	154984.9	199226.3
7	4	15157	6	4454	0	0	56875.80	178890.5
8	3	14248	5	7968	0	0	213865.8	183262.4
9	2	14196	4	10872	0	0	161064.2	180795.9
10	1	14284	4	14200	0	0	57789.61	168495.3

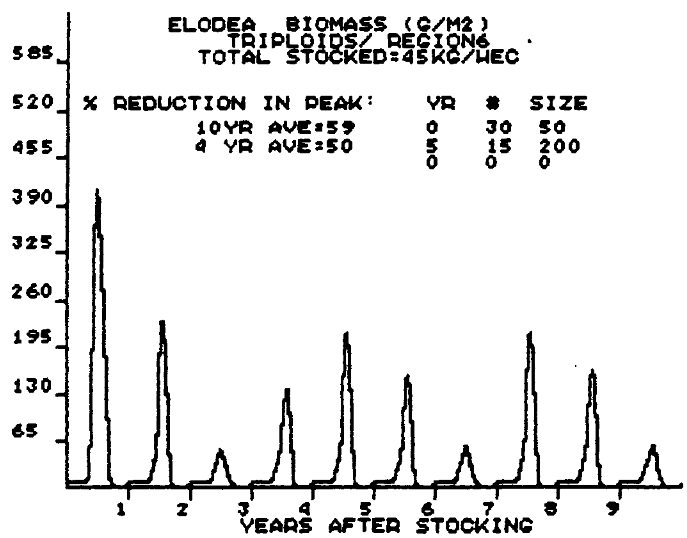


Fig. A2-14. Eradication of Elodea canadensis in Region 6.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	30	3270	0	0	0	0	394636.8	394636.8
2	20	7804	0	0	0	0	52682.95	223659.8
3	13	14279	0	0	0	0	52720.16	166679.9
4	9	18727	0	0	0	0	52657.68	138174.4
5	7	22915	0	0	0	0	52556.24	121050.7
6	5	26446	0	0	0	0	52528.04	109630.2
7	4	23636	15	1481	0	0	82854.62	105805.2
8	3	20232	12	3601	11	973	79888.96	102565.6
9	2	16737	9	7799	7	336	55947.16	97385.81
10	1	14365	6	14641	2	473	51185.95	92765.82

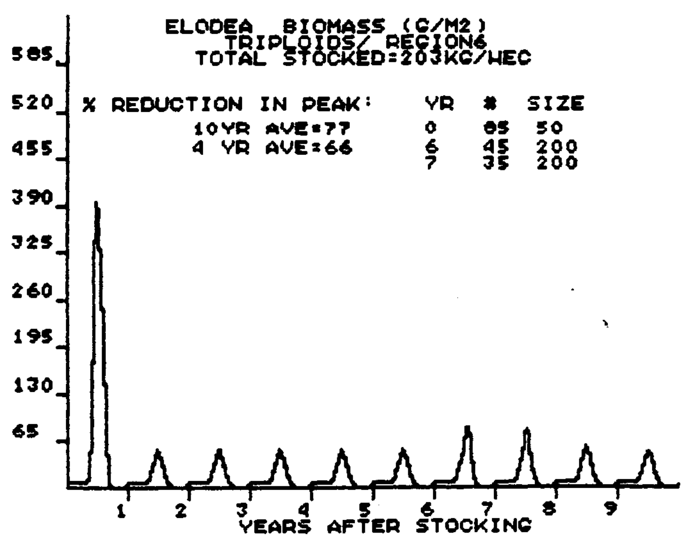


Fig. A2-15. BMP control of <u>Elodea canadensis</u> in Region 11.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	11	3372	0	0	0	0	403919.5	403919.5
2	10	3337	0	0	0	0	213152.5	308536.0
3	7	15708	0	0	0	0	48322.39	221798.1
4	7	14565	0	0	0	0	128363.6	198439.5
5	6	14504	7	2382	0	0	154683.5	189688.3
6	5	15280	5	3615	0	0	45525.33	165661.1
7	4	14465	4	7149	0	0	187670.7	168805.3
8	3	14472	3	10277	0	0	146744.1	166047.7
9	2	14253	3	12974	0	0	202998.1	170153.3
10	1	14075	3	14145	0	0	147045.3	167842.4

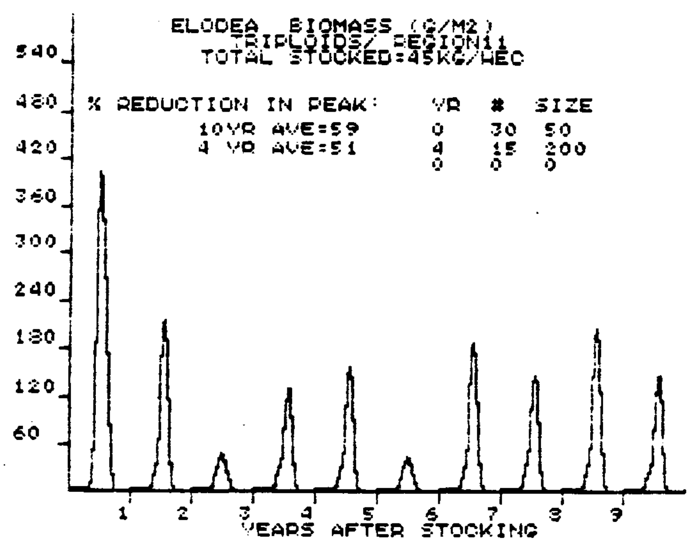


Fig. A2-16. Eradication of _Elodea canadensis_ in Region 11.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	52	3064	0	0	0	0	367979.8	367979.8
2	34	5376	0	0	0	0	48573.98	208276.9
3	21	9011	0	0	0	0	48643.06	155065.6
4	13	14642	0	0	0	0	48522.24	128429.7
5	9	18653	0	0	0	0	48494.40	112442.6
6	7	22458	0	0	0	0	48337.36	101758.4
7	4	23137	8	421	0	0	48179.48	94104.29
8	3	20272	7	2610	5	1266	64743.54	90434.21
9	2	17038	6	5830	4	1969	54344.86	86424.27
10	1	14355	4	9595	2	2354	51882.45	82970.10

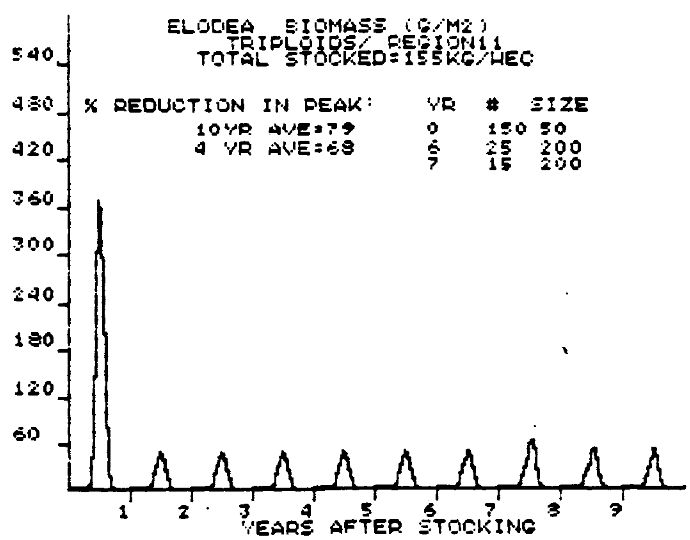


Fig. A2-17. BMP control of Elodea canadensis in Region 15.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	10	3865	0	0	0	0	391555.5	391555.5
2	7	9192	0	0	0	0	54244.69	222900.1
3	5	13966	0	0	0	0	63433.97	169744.7
4	4	13901	0	0	0	0	208512.9	179436.7
5	4	14044	0	0	0	0	260587.3	195666.8
6	3	13908	11	3355	0	0	239422.5	202959.4
7	2	14025	6	5166	0	0	41523.06	179897.1
8	1	13576	4	9324	0	0	38285.91	162195.7
9	1	13740	3	13311	0	0	168081.2	162849.6
10	1	13783	2	13724	0	0	123264.6	158891.1

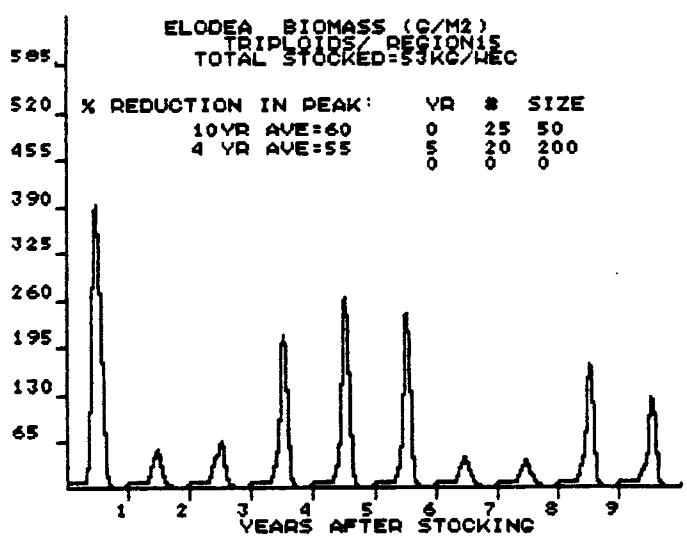


Fig. A2-18. Eradication of <u>Elodea canadensis</u> in Region 15.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
2	24	5064	0	0	0	0	48555.07	200231.3
3	13	9097	0	0	0	0	48577.78	149680.1
4	8	15089	0	0	0	0	48516.91	124389.3
5	6	14394	0	0	0	0	62665.10	112044.4
6	4	14027	29	910	0	0	67392.21	104602.4
7	2	13839	18	2307	0	0	65761.87	99053.79
8	1	13800	11	4240	0	0	50918.29	93036.85
9	1	13750	7	8985	0	0	55912.02	88911.84
10	1	13478	4	14072	0	0	38952.75	83915.94

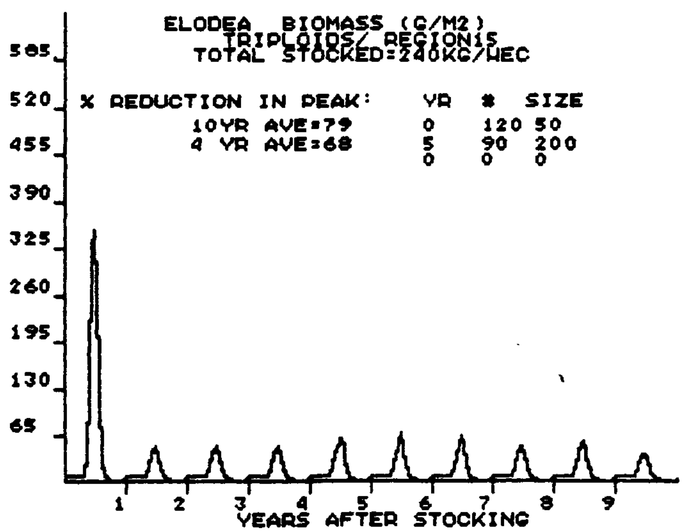


Fig. A2-19. BMP control of *Elodea canadensis* in Region 19.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	11	14019	0	0	0	0	384846.1	384846.1
2	7	9768	0	0	0	0	44513.15	214679.6
3	5	13208	0	0	0	0	69816.81	166392.0
4	4	13534	0	0	0	0	198090.8	174316.7
5	3	13395	0	0	0	0	246443.8	188742.1
6	3	13463	7	2986	0	0	247955.4	198610.9
7	2	13356	6	6609	0	0	152366.1	192004.6
8	1	12998	4	10484	0	0	78198.43	177778.8
9	1	13169	3	12957	0	0	63872.04	165122.5
10	0	15269	2	13062	0	0	49005.32	153510.7

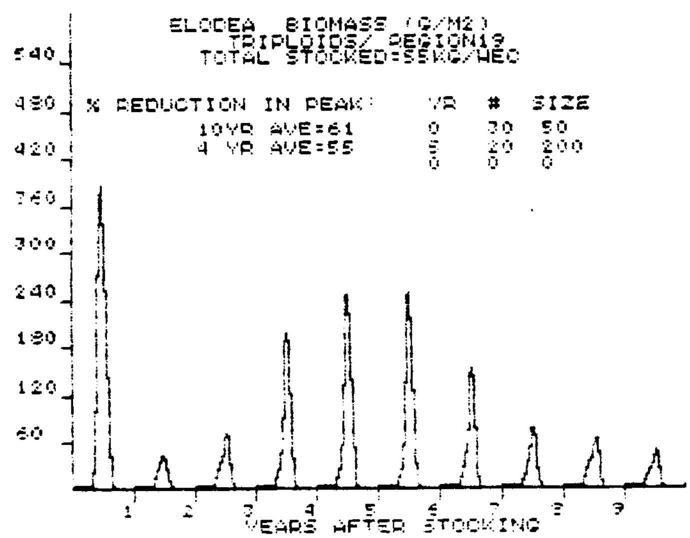


Fig. A2-20. Eradication of *Elodea canadensis* in Region 19.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	49	2686	0	0	0	0	335032.3	335032.3
2	27	3896	0	0	0	0	48342.73	191687.5
3	15	6752	0	0	0	0	48364.83	143913.3
4	8	12326	0	0	0	0	48399.92	120034.9
5	6	13311	0	0	0	0	67119.00	109451.7
6	4	13412	24	1020	0	0	79505.96	104460.7
7	2	13112	16	2332	0	0	73257.40	100003.1
8	1	13022	9	4146	0	0	47118.29	93392.53
9	1	13053	6	7659	0	0	69116.26	90695.16
10	0	14476	3	12836	0	0	35194.91	85145.13

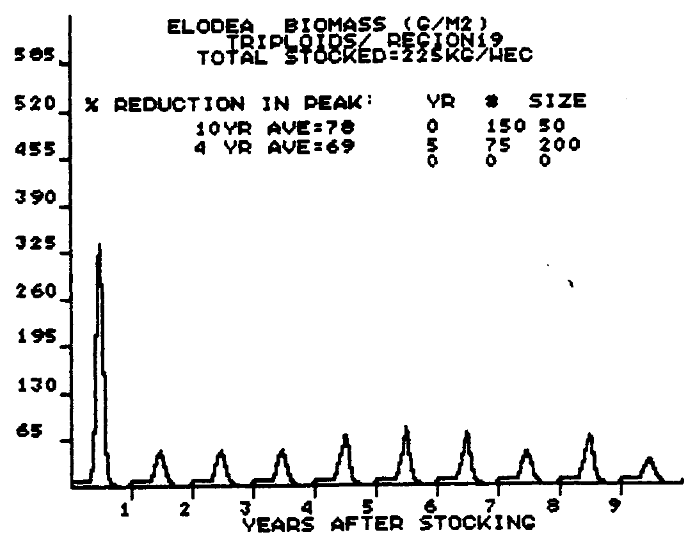


Fig. A2-21. BMP control of <u>Ceratophyllum demersum</u> in Region 1.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	23	920	0	0	0	0	161098.6	161098.6
2	22	1726	0	0	0	0	136300.7	148699.6
3	19	2528	0	0	0	0	20125.10	105841.4
4	16	3760	0	0	0	0	18518.58	84010.75
5	12	5342	0	0	0	0	18584.19	70925.44
6	9	7388	0	0	0	0	18567.36	62199.09
7	6	9987	0	0	0	0	18546.17	55962.95
8	4	10665	0	0	0	0	19025.87	51345.82
9	3	9760	0	0	0	0	103175.8	57104.70
10	2	8701	0	0	0	0	147568.2	66151.05

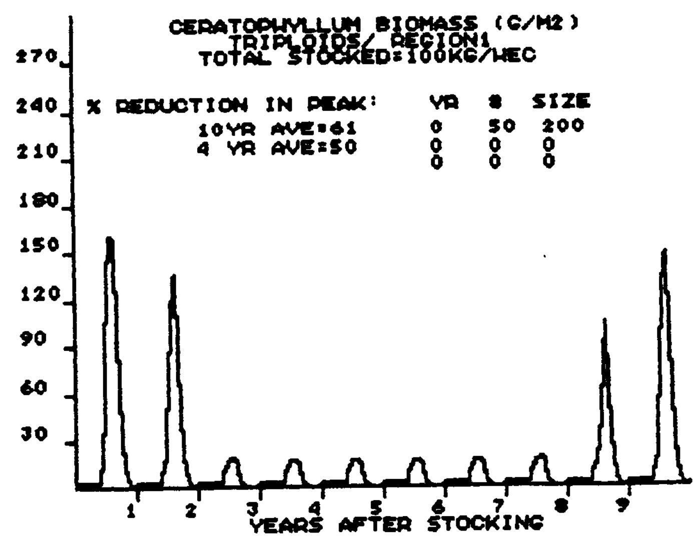


Fig. A2-22. Eradication of <u>Ceratophyllum demersum</u> in Region 1.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	105	750	0	0	0	0	26118.05	26118.05
2	80	1061	0	0	0	0	18577.90	22347.98
3	58	1440	0	0	0	0	18578.60	21091.52
4	43	1947	0	0	0	0	18586.55	20465.28
5	31	2628	0	0	0	0	18574.88	20087.19
6	22	3559	0	0	0	0	18577.55	19835.59
7	14	4936	0	0	0	0	18635.54	19664.15
8	8	6825	0	0	0	0	18567.76	19527.10
9	5	8017	0	0	0	0	18536.52	19417.03
10	3	7723	0	0	0	0	100166.6	27491.99

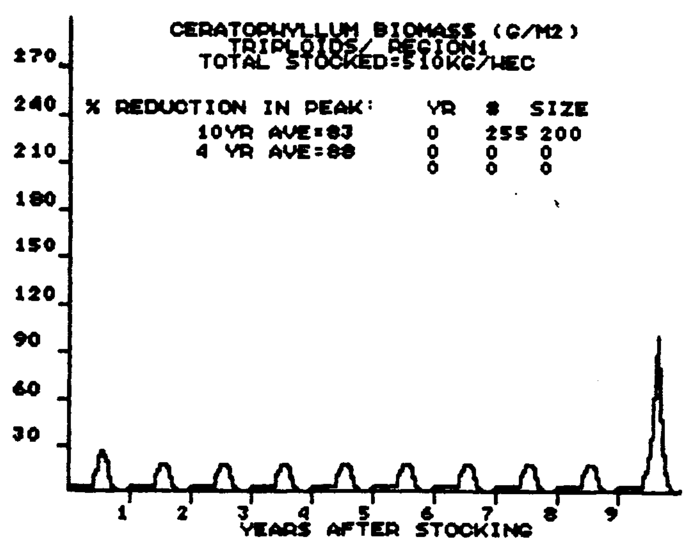


Fig. A2-23. BMP control of *Ceratophyllum demersum* in Region 6.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	12	1346	0	0	0	0	170786.2	170786.2
2	11	2678	0	0	0	0	154148.5	162467.4
3	10	3933	0	0	0	0	107260.1	144064.9
4	9	6678	0	0	0	0	22465.33	113665.0
5	6	11108	0	0	0	0	22497.16	95431.47
6	5	14296	0	0	0	0	22495.09	83275.41
7	3	14379	0	0	0	0	29089.10	75534.50
8	2	14322	9	945	0	0	24026.19	69095.96
9	2	13013	8	1883	0	0	29741.83	64723.28
10	1	11195	8	3027	0	0	134546.9	71705.65

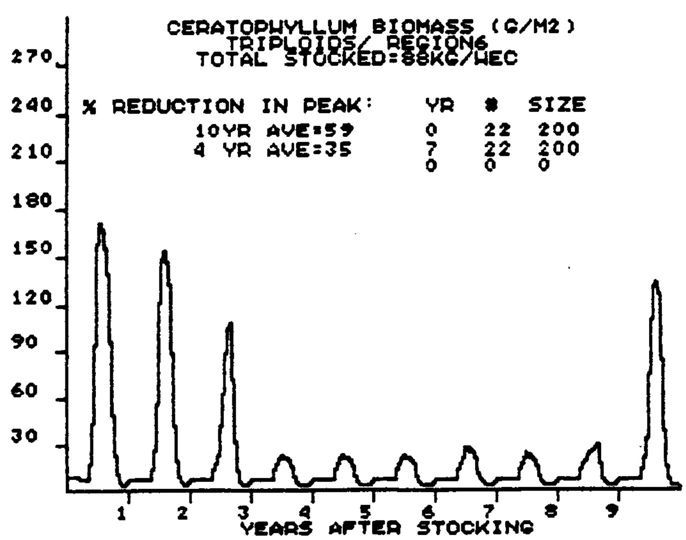


Fig. A2-24. Eradication of <u>Ceratophyllum demersum</u> in Region 6.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	24	1340	0	0	0	0	164472.7	164472.7
2	22	2841	0	0	0	0	25657.94	95065.36
3	16	4947	0	0	0	0	22451.75	70860.83
4	11	7801	0	0	0	0	22454.10	58759.15
5	8	11876	0	0	0	0	22457.65	51498.84
6	5	14543	0	0	0	0	22454.81	46658.17
7	4	14348	0	0	0	0	29020.78	44138.54
8	3	14317	0	0	0	0	24858.31	41728.51
9	2	13043	41	827	0	0	32106.81	40659.43
10	1	11992	33	1757	0	0	26718.20	39265.30

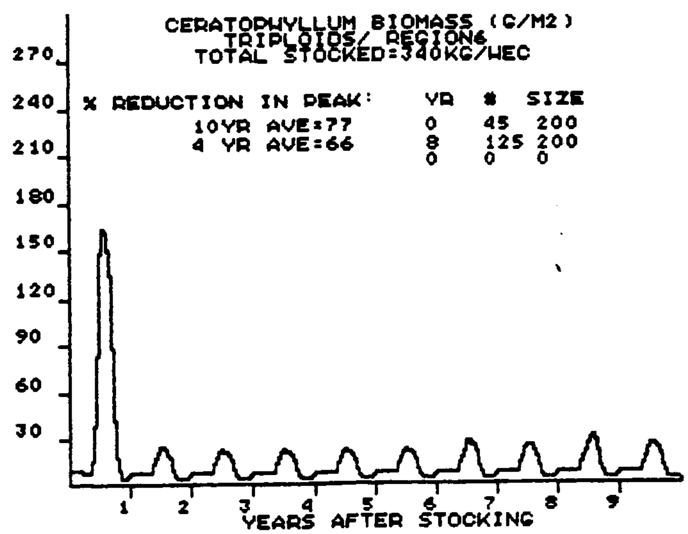


Fig. A2-25. BMP control of _Ceratophyllum demersum_ in Region 11.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS S
0	0	0	4	0	0	0	0	
1	11	1353	0	0	0	0	167337.8	167337.8
2	10	2683	0	0	0	0	152804.1	160071.0
3	9	3915	0	0	0	0	119054.5	146398.8
4	8	6089	0	0	0	0	19159.18	114588.9
5	6	9934	0	0	0	0	18864.48	95444.04
6	5	14255	0	0	0	0	18951.98	82695.34
7	3	14301	0	0	0	0	25589.84	74537.42
8	2	14056	9	896	0	0	20263.34	67753.17
9	1	12764	8	1887	0	0	23996.45	62891.30
10	1	10967	7	3033	0	0	130597.0	69661.87

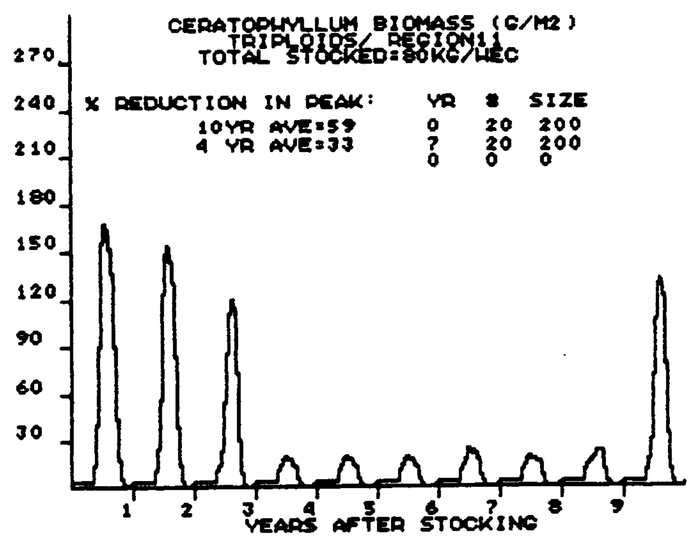


Fig. A2-26. Eradication of <u>Ceratophyllum</u> <u>demersum</u> in Region 11.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	24	1347	0	0	0	0	160584.8	160584.8
2	22	2786	0	0	0	0	23583.39	92084.12
3	16	4798	0	0	0	0	18856.99	67675.06
4	11	7493	0	0	0	0	18925.15	55487.59
5	8	11377	0	0	0	0	18923.11	48174.69
6	5	14570	0	0	0	0	18933.63	43301.18
7	4	14321	0	0	0	0	25670.12	40782.46
8	3	14274	0	0	0	0	20864.64	38292.73
9	2	12978	43	805	0	0	28825.60	37240.82
10	1	11851	34	1671	0	0	23087.59	35825.50

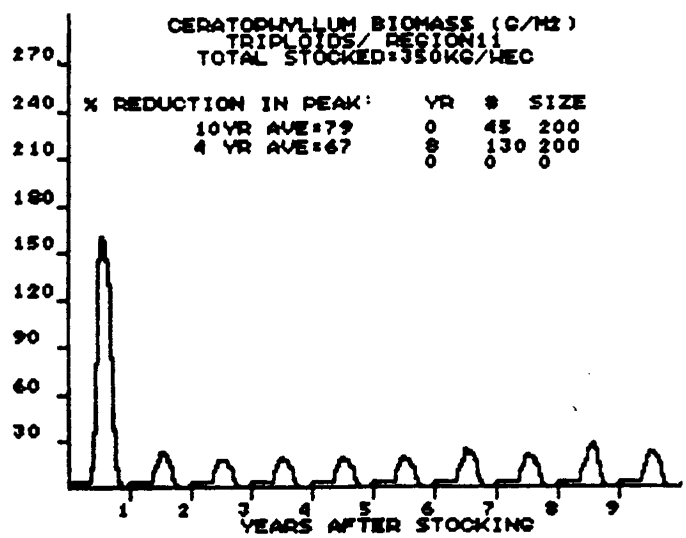


Fig. A2-27. BMP control of <u>Ceratophyllum demersum</u> in Region 15.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	12	1646	0	0	0	0	165301.0	165301.0
2	11	3279	0	0	0	0	133314.9	149307.9
3	9	5747	0	0	0	0	22558.05	107057.9
4	6	9892	0	0	0	0	22055.19	85807.28
5	4	14323	0	0	0	0	21935.59	73032.95
6	3	14024	0	0	0	0	29747.38	65818.69
7	2	14063	0	0	0	0	25362.06	60039.17
8	2	12601	11	1317	0	0	90125.76	63799.99
9	1	11094	10	2759	0	0	127070.1	70830.00
10	1	10173	7	4638	0	0	21157.84	65862.78

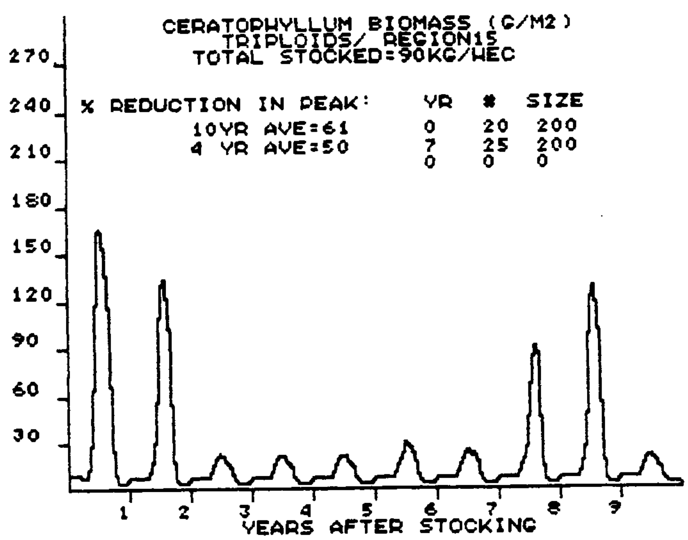


Fig. A2-28. Eradication of <u>Ceratophyllum</u> <u>demersum</u> in Region 15.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	26	1625	0	0	0	0	155650.5	155650.5
2	19	3252	0	0	0	0	21927.76	88789.15
3	12	5444	0	0	0	0	21962.75	66513.69
4	8	8800	0	0	0	0	21977.19	55379.56
5	5	14004	0	0	0	0	22061.46	48715.94
6	4	14036	0	0	0	0	29357.03	45489.44
7	3	14018	0	0	0	0	25128.52	42580.75
8	2	12865	33	808	0	0	34870.72	41616.99
9	1	12056	24	1702	0	0	26417.92	39928.20
10	1	10849	15	2655	0	0	22167.60	38152.14

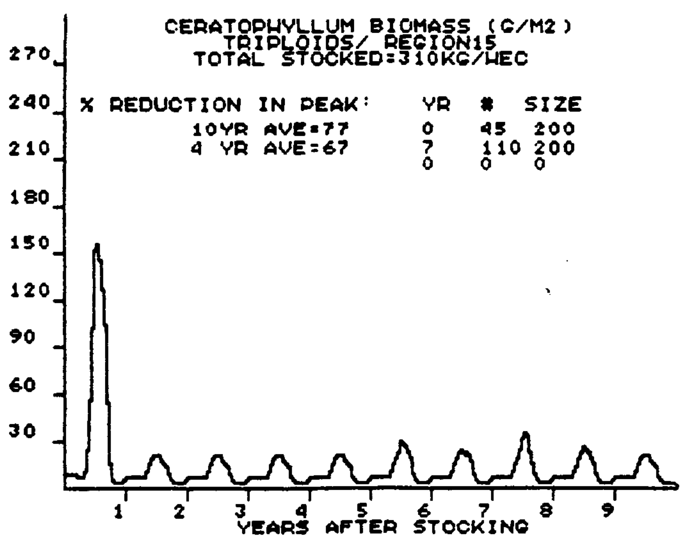


Fig. A2-29. BMP control of <u>Ceratophyllum demersum</u> in Region 19.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	9	2062	0	0	0	0	162651.5	162651.5
2	9	4172	0	0	0	0	132353.5	147502.4
3	6	7449	0	0	0	0	18433.42	104479.4
4	4	13054	0	0	0	0	18356.05	82948.61
5	3	14384	0	0	0	0	24753.23	71309.53
6	3	14331	0	0	0	0	23142.15	63281.63
7	2	13553	0	0	0	0	97371.29	68151.58
8	1	12806	8	1940	0	0	51790.59	66106.46
9	1	11685	8	3869	0	0	109231.2	70898.11
10	1	12475	5	5529	0	0	16814.41	65489.74

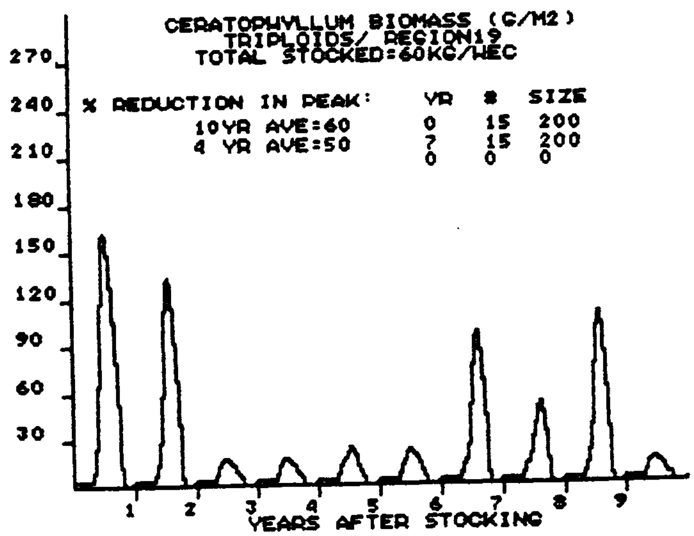


Fig. A2-30. Eradication of <u>Ceratophyllum demersum</u> in Region 19.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	29	2023	0	0	0	0	149083.8	149083.8
2	19	3343	0	0	0	0	18407.43	83745.60
3	12	5383	0	0	0	0	18462.69	61984.63
4	7	8701	0	0	0	0	18438.47	51098.09
5	5	14016	0	0	0	0	18471.22	44572.72
6	4	14349	0	0	0	0	26250.44	41519.01
7	3	14302	0	0	0	0	22901.19	38859.31
8	2	14238	22	853	0	0	32466.73	38060.24
9	1	13096	18	1856	12	288	30234.28	37190.68
10	1	13266	11	2632	0	125	18328.51	35304.47

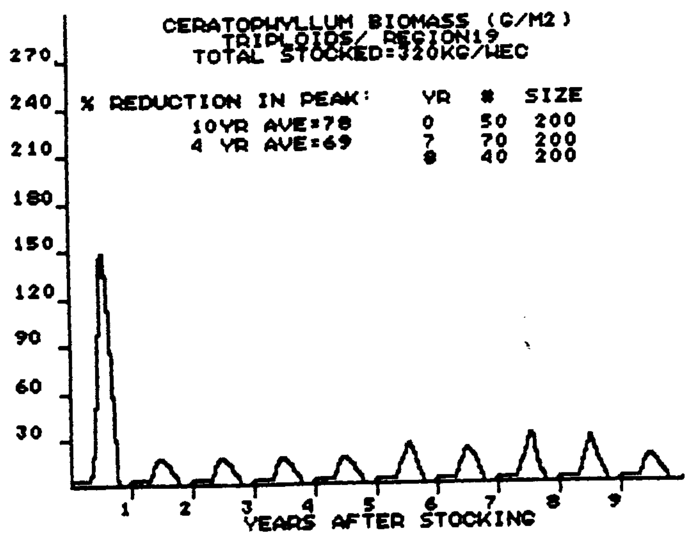


Fig. A2-31. BMP control of *Myriophyllum* spp. in Region 1.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	26	578	0	0	0	0	198092.3	198092.3
2	26	958	0	0	0	0	157943.2	178017.8
3	23	1306	0	0	0	0	102462.0	152832.5
4	21	1605	0	0	0	0	55264.01	128440.4
5	20	1875	0	0	0	0	26057.81	107963.8
6	17	2130	0	0	0	0	16629.46	92741.46
7	13	2317	0	0	0	0	34201.66	84378.62
8	9	2449	13	480	0	0	64130.07	81847.57
9	6	2554	12	801	0	0	101614.3	84043.85
10	4	2628	11	1116	0	0	124166.6	88056.13

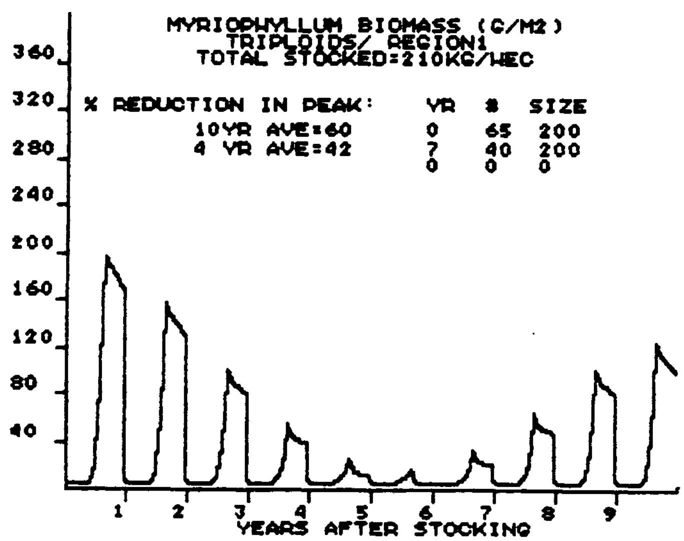


Fig. A2-32. Eradication of <u>Myriophyllum</u> spp. in Region 1.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	52	572	0	0	0	0	161719.1	161719.1
2	50	936	0	0	0	0	30229.88	95974.47
3	41	1304	0	0	0	0	10330.24	67426.39
4	33	1680	0	0	0	0	10326.19	53151.34
5	26	2105	0	0	0	0	10329.81	44587.03
6	20	2595	0	0	0	0	10332.06	38877.87
7	14	3122	0	0	0	0	10344.01	34801.60
8	9	3163	0	0	0	0	19908.79	32940.00
9	6	3149	40	439	0	0	16226.84	31082.98
10	4	3098	35	740	0	0	36362.14	31610.89

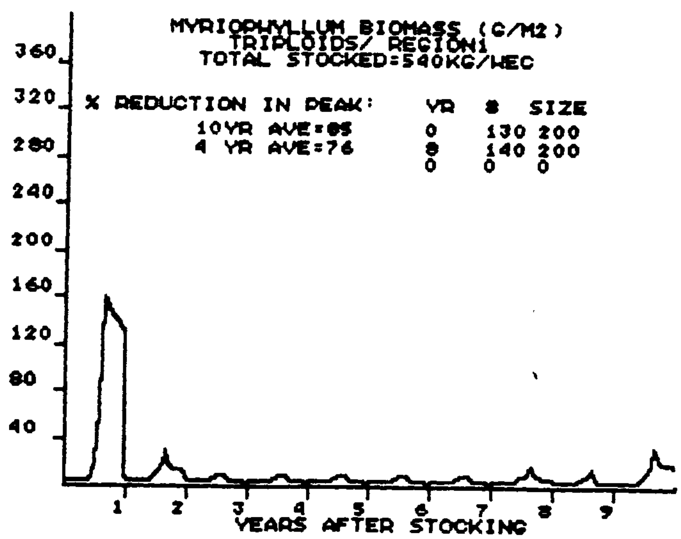


Fig. A2-33. BMP control of <u>Myriophyllum</u> spp. in Region 6.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	18	771	0	0	0	0	246350.0	246350.0
2	17	1367	0	0	0	0	210045.7	228197.8
3	16	1909	0	0	0	0	139382.1	198592.6
4	15	2370	0	0	0	0	68372.89	166037.6
5	13	3022	0	0	0	0	15139.56	135858.0
6	11	3823	0	0	0	0	13986.71	115546.1
7	8	4498	0	0	0	0	14977.78	101179.2
8	5	4501	12	616	0	0	46693.56	94368.55
9	4	4404	11	1124	0	0	119216.0	97129.35
10	3	4279	10	1612	0	0	137599.6	101176.3

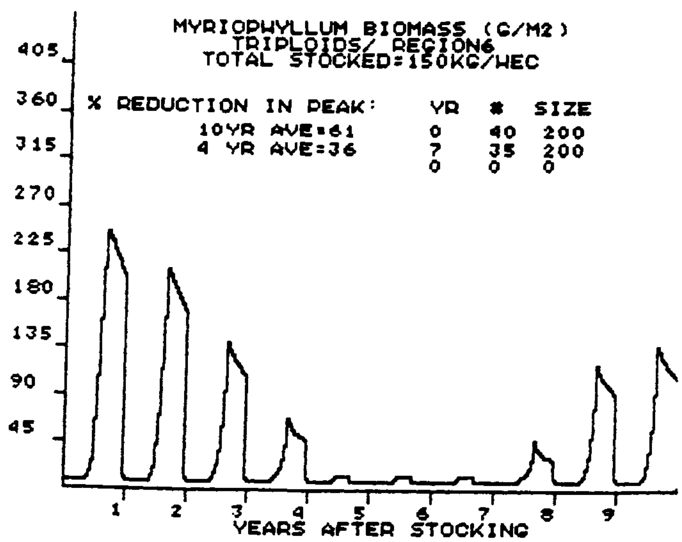


Fig. A2-34. Eradication of Myriophyllum spp. in Region 6.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	20	766	0	0	0	0	223956.6	223956.6
2	36	1345	0	0	0	0	28425.07	126190.8
3	28	1992	0	0	0	0	13831.90	88737.85
4	21	2719	0	0	0	0	13837.26	70012.71
5	16	3605	0	0	0	0	13825.27	58775.21
6	12	4709	0	0	0	0	13851.33	51287.89
7	8	5972	0	0	0	0	13867.08	45942.05
8	5	6563	0	0	0	0	14559.93	42019.30
9	3	5941	25	583	0	0	46147.91	42478.02
10	2	5416	23	1067	0	0	43076.94	42537.92

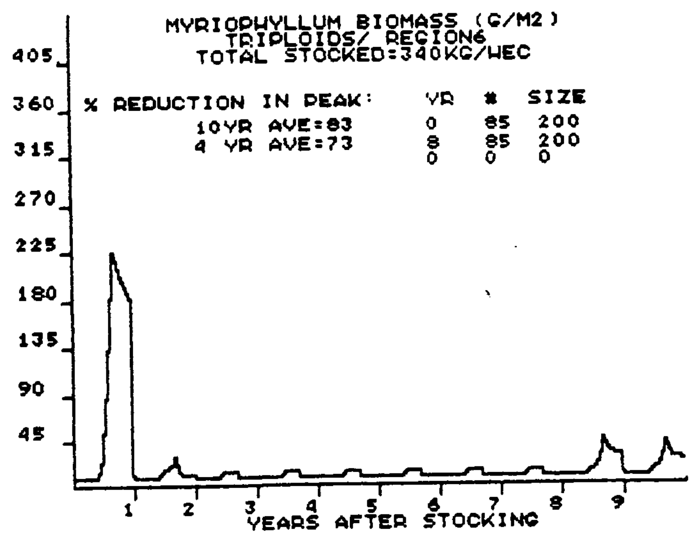


Fig. A2-35. BMP control of Myriophyllum spp. in Region 11.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	20	773	0	0	0	0	257700.6	257700.6
2	20	1361	0	0	0	0	221555.8	239628.2
3	18	1895	0	0	0	0	132129.1	203795.1
4	16	2619	0	0	0	0	14315.67	156425.2
5	13	3616	0	0	0	0	13805.01	127901.2
6	10	4819	0	0	0	0	13808.35	108885.7
7	7	5912	0	0	0	0	14324.82	95377.03
8	5	5815	4	609	0	0	35171.49	87851.35
9	3	5336	3	1097	0	0	159970.0	95864.51
10	2	4941	3	1632	0	0	207774.4	107055.5

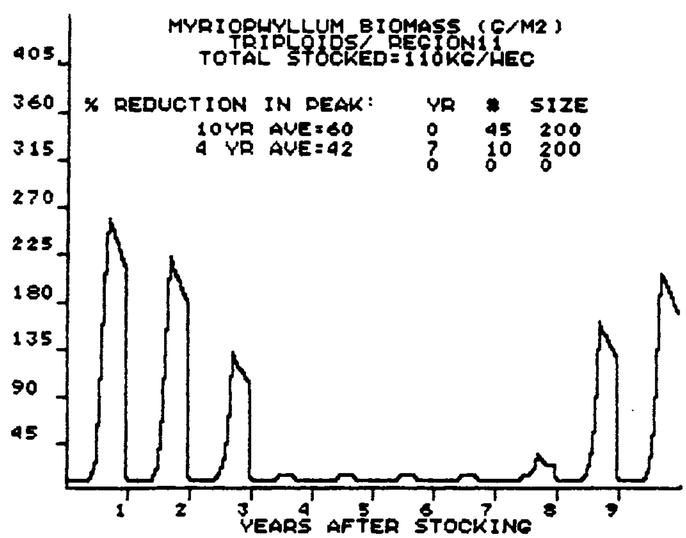


Fig. A2-36. Eradication of *Myriophyllum* spp. in Region 11.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	38	768	0	0	0	0	240706.9	240706.9
2	36	1342	0	0	0	0	44752.15	142729.5
3	28	2054	0	0	0	0	13829.45	99762.83
4	21	2853	0	0	0	0	13835.49	78281.00
5	16	3834	0	0	0	0	13835.08	65391.80
6	11	5081	0	0	0	0	13842.69	56800.28
7	7	6543	0	0	0	0	13852.15	50664.83
8	5	6988	0	0	0	0	17086.97	46467.60
9	3	6232	24	570	0	0	30583.80	44702.73
10	2	5598	22	1061	0	0	27996.66	43032.12

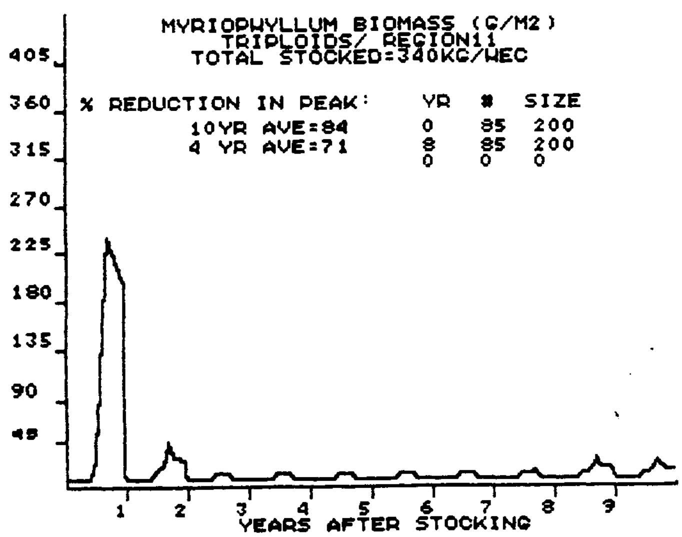


Fig. A2-37. BMP control of Myriophyllum spp. in Region 15.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	13	931	0	0	0	0	266317.0	266317.0
2	17	1661	0	0	0	0	234450.6	250383.8
3	15	2300	0	0	0	0	132732.0	211166.5
4	13	3328	0	0	0	0	13791.11	161822.6
5	10	4655	0	0	0	0	13825.33	132223.2
6	7	6335	0	0	0	0	13790.32	112484.3
7	5	7284	0	0	0	0	14691.39	98513.94
8	3	6542	8	699	0	0	68766.02	94795.46
9	2	5884	7	1389	0	0	174019.7	103598.1
10	1	5398	6	2023	0	0	207873.4	114025.6

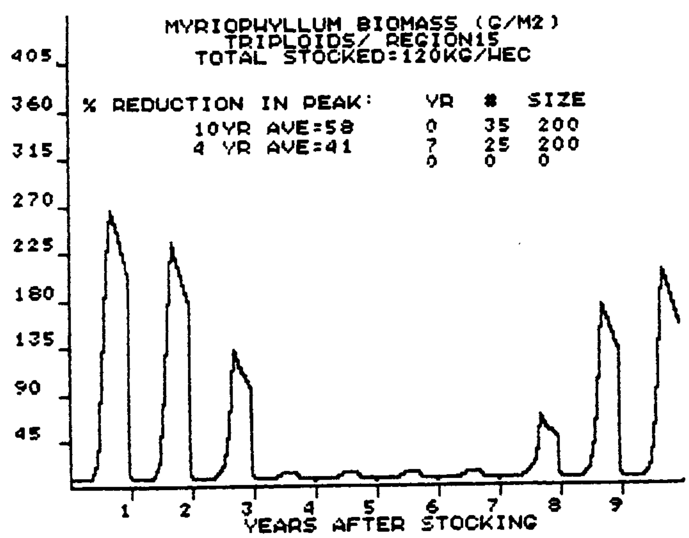


Fig. A2-38. Eradication of *Myriophyllum* spp. in Region 15.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	44	922	0	0	0	0	240394.2	240394.2
2	34	1672	0	0	0	0	13805.46	127099.8
3	24	2476	0	0	0	0	13816.92	89338.85
4	17	3522	0	0	0	0	13820.51	70459.28
5	12	4907	0	0	0	0	13819.04	59131.22
6	8	6705	0	0	0	0	13828.35	51580.73
7	5	8440	0	0	0	0	13862.93	46192.47
8	3	8155	0	0	0	0	16930.04	42534.67
9	2	7076	30	746	0	0	26566.47	40760.43
10	1	6412	24	1344	0	0	13188.38	38003.22

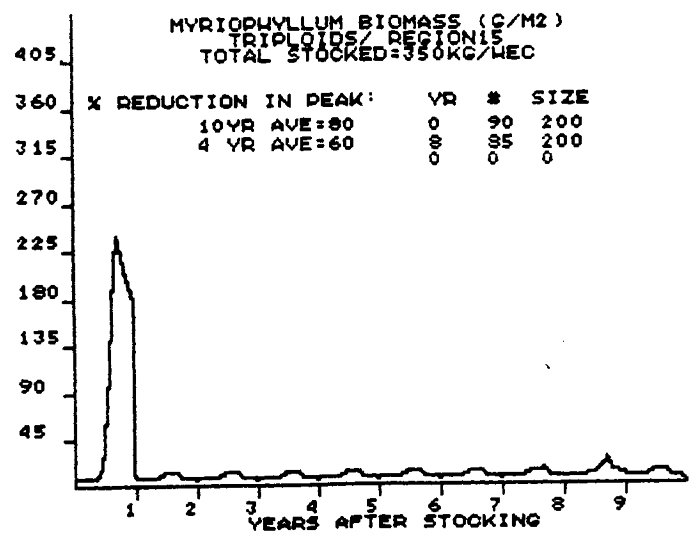


Fig. A2-39. BMP control of Myriophyllum spp. in Region 19.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	13	1153	0	0	0	0	274870.3	274870.3
2	12	2130	0	0	0	0	258719.8	266795.1
3	11	2968	0	0	0	0	184952.3	239514.2
4	10	4636	0	0	0	0	10289.03	182207.8
5	7	7051	0	0	0	0	10287.78	147823.8
6	5	10232	0	0	0	0	10339.94	124909.8
7	3	13375	0	0	0	0	10421.35	108554.3
8	2	11344	10	808	0	0	85099.70	105622.5
9	1	9775	9	1741	0	0	9365.656	94927.32
10	1	8161	8	2575	0	0	226342.0	108068.7

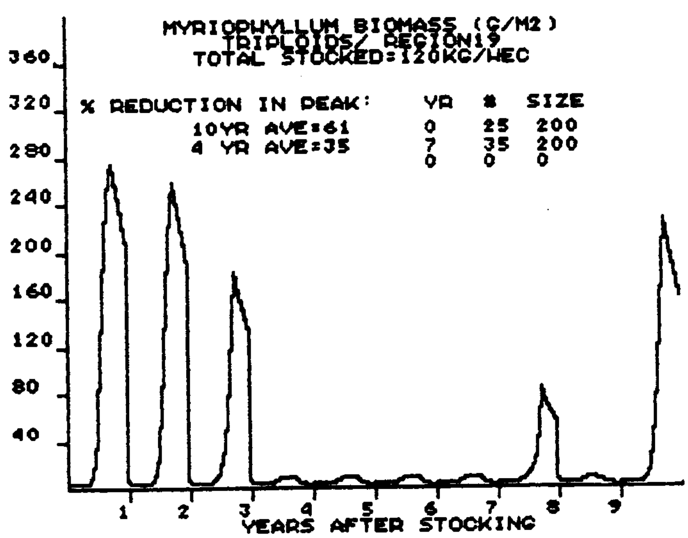


Fig. A2-40. Eradication of Myriophyllum spp. in Region 19.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	86	1100	0	0	0	0	23069.15	23069.15
2	57	1313	0	0	0	0	10312.62	16690.88
3	37	1853	0	0	0	0	10312.09	14564.62
4	24	2707	0	0	0	0	10315.19	13502.26
5	17	3949	0	0	0	0	10312.61	12864.33
6	11	5795	0	0	0	0	10330.14	12441.97
7	6	8610	0	0	0	0	10351.14	12143.27
8	3	11743	0	0	0	0	10308.28	11913.90
9	2	12191	0	0	0	0	22824.65	13126.21
10	2	9888	0	0	0	0	218705.5	33684.13

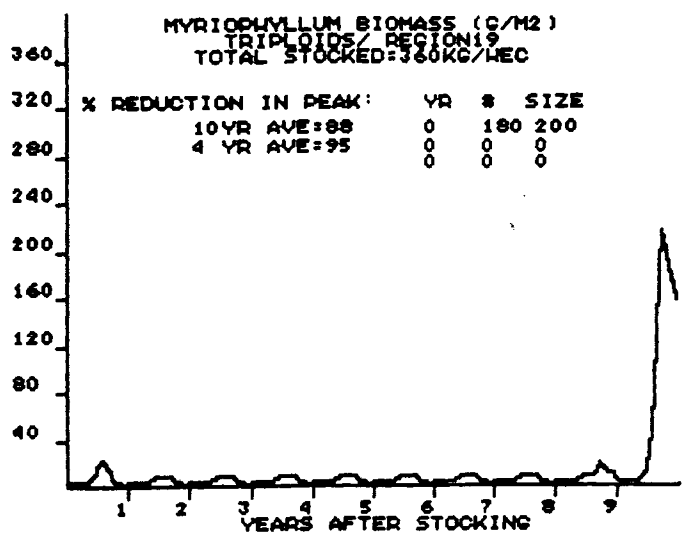


Fig. A2-41. BMP control of <u>Potamogeton crispus</u>/<u>Najas flexilis</u> in Region 11.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	4	5787	0	0	0	0	237456.5	237456.5
2	3	11379	0	0	0	0	35716.47	136586.4
3	2	18775	0	0	0	0	19901.19	97691.36
4	1	26075	0	0	0	0	54466.08	86885.04
5	0	0	0	0	0	0	91744.82	87857.00
6	0	0	4	5436	0	0	244004.5	113881.5
7	0	0	2	12218	0	0	59900.28	106169.9
8	0	0	2	18837	0	0	29138.03	96540.97
9	0	0	1	27462	0	0	87479.42	95534.11
10	0	0	0	-24639	0	0	85176.62	94498.36

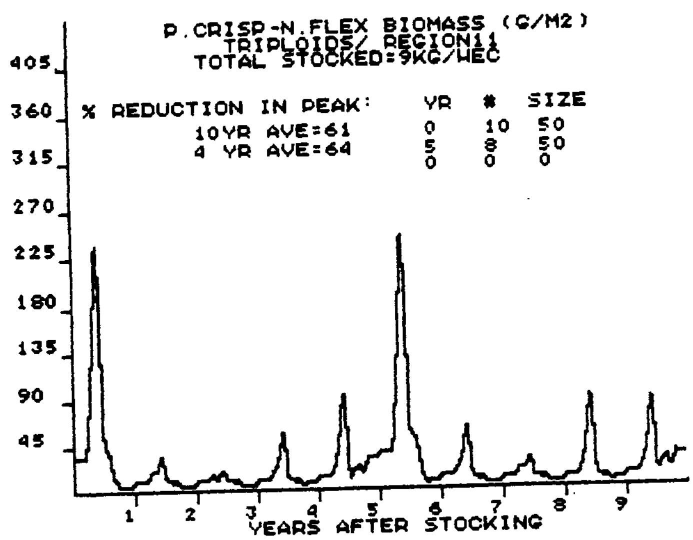
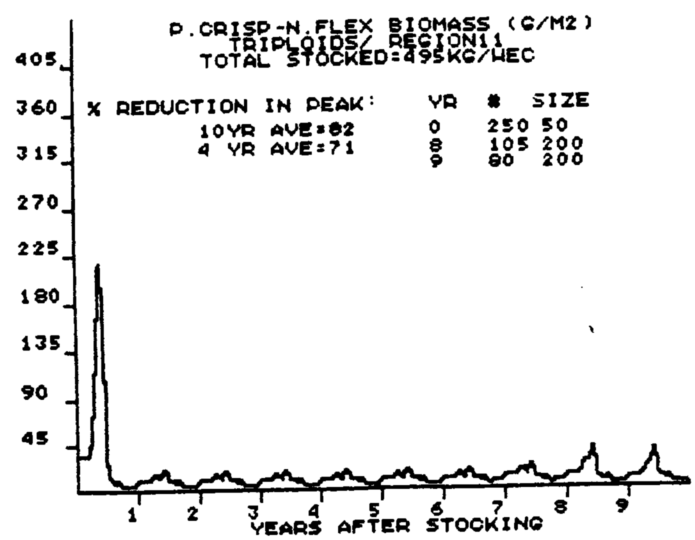


Fig. A2-42. Eradication of Potamogeton crispus/Najas flexilis in Region 11.

YEAR	FNUM	SIZE	FNUM2	SIZE2	FNUM3	SIZE3	PEAK BIOMASS	MEAN BIOMASS
1	58	494	0	0	0	0	218552.6	218552.6
2	35	911	0	0	0	0	21572.70	120062.6
3	21	1573	0	0	0	0	20301.57	86808.96
4	12	2743	0	0	0	0	20178.66	70151.39
5	7	4766	0	0	0	0	20000.44	60121.20
6	4	8436	0	0	0	0	19914.03	53420.00
7	2	14851	0	0	0	0	19892.59	48630.37
8	1	21911	0	0	0	0	23734.11	45518.34
9	1	29593	18	284	0	0	39904.27	44894.55
10	0	29593	9	2741	4	55	37029.85	44108.07



APPENDIX 3. Source Code Listing for IHF3S

note: these listings are for illustrative purposes only. Code for portions of the User Interface, graphics routines, floating point operators and other non-standard FORTH words are not included. For a compilable listing of the system please contact:

Dr. M. J. Wiley
Aquatic Biology Section
Illinois Natural History Survey
Champaign, Illinois, 61820.

```
( ---------------------------------------------------------- )
( ---------------------------------------------------------- )
(       HERBIVOROUS CARP BIOENERGETIC GROWTH SUBMODEL        )
(                    - IHF3S.NHS                             )
( ----------------------------------------------------------)
( ----------------------------------------------------------)

          ( AUXILLARY EQUATIONS )

: TTC FSAV WTEM F@ LN    C24 F@ F* C25    ( temp correction  func
  F@ F+  TSCAL F! FRES ;                    for consumption )

: DTC TSCAL F@ C26 F@ F/ F* ;             ( scale temp correction )

: WTC WTEM F@ C12 F* C13 F+ EXP F/ ;       ( Winberg temp correction
                                            for respiration  )

FVAR TRCONCV .90
: TRIPCHK  TRIP? @ 1 =                    ( if triploid lower consumption
               IF TRCONCV F@ F*               by trconv )
               THEN ;


: FOODCHECK FSAV                         ( see if food is available )
    PLANT1 F@ ZVAR F@ F=
         IF             STARVE F@
      ELSE FRES THEN ;


FVAR PAVAIL 0
FVAR PAVAILO 10000000
FVAR ZVAR2 5000
: SELPLANT1 1 P1SEL ! 0 P2SEL ! PLANT1       ( select plant1 to be consumed )
   F@ ZVAR F@ F- PAVAIL F! ;
: SELPLANT2 0 P1SEL ! 1 P2SEL !  PLANT2      ( select plant2 to be consumed )
   F@ ZVAR2 F@ F- PAVAIL F! ;
: SELNONE   0 P1SEL ! 0 P2SEL ! PAVAILO    ( select no plants to be consumed)
  F@ PAVAIL F! ;

: NOSTARVE 0 STARV? ! ;  ( resets starvation flag )


: STARVING 1 STARV? ! ;  ( set starvation flag )


: PLANTCHECK      ( decides which plant should be eaten and sets
                    starvation flags )
 FSAV PLANT2 F@ ZVAR2 F@ F<   ( save fstack and begin)
     IF FRES P2CRATE F@ F* SELPLANT2
        ELSE PLANT1 F@ ZVAR F@ F<
```

```
          IF FRES  SELPLANT1
        ELSE SELNONE STARVING
       FRES STARVE F@ F*
   THEN THEN ;
FVAR HUNGER 0

: AMOUNTCHECK           ( gets amount available of selected plant )
   FSAV FDUP PAVAIL F@ F<
   IF FSWAP PAVAIL F@ FSWAP F/ ONE FSWAP
   F- HUNGER F!
   PAVAIL F@ STARVING
   ELSE ZERO HUNGER F! FRES THEN ;


               ( RATE EQUATIONS )

FVAR W10 1.42
FVAR W11 .000306589
FVAR C45 -.000080
FVAR C42 .42
15000  VARIABLE THRS
FVAR C35 -.000000232
FVAR C36 .0003417
FVAR C37 .363
: CONSMP              ( calculates consumption for group I )
 I SIZE F@ FIXS THRS @ <
        IF
           C42 F@
         TTC DTC ZCHECK
        ELSE
            C42 F@
           TWO F/     ( halves ingestion for > 15 kg )
           TTC     DTC
        THEN ( SMALLCHECK )  TRIPCHK
          I SIZE F@ F*
    AMOUNTCHECK ZCHECK FDUP I CONWT
    F! FDUP PAVAIL F@ FSWAP F- PAVAIL
      F!  PLANTCALS I CONSUMP F! ;

: ACTIVITY             ( metabolism increment due to activity. Assumed to
                         be  dependent on feeding rate and therefore
                         inderctly on temperature )
 STARV? @ 1 = IF
 TSCAL F@  MAXACT F/ TWO F/
                  ELSE TSCAL F@
```

```
                          MAXACT F/
THEN RTMB F@ F* 1 FLTS F+     ZCHECK
        RTM F! ;


FVAR C60 .066 ( SDA )
FVAR W3 25.4163

: RESP                                ( respiration for group I )
  ACTIVITY I SIZE F@ W1 F@ F^ W3 F@ F*
     W2 F@    F* FDUP WSCALE F! WTC
       RTM F@ F* O2CONV
  F* ZCHECK I CONSUMP F@ C60 F@ F* F+
    I  RESPIRE F! ;


FVAR MAXASSIM .45
FVAR C40 1.34
FVAR C41 1.9699
FVAR STVASSIM .2 ( % INCREASE AT STARV )
FVAR C47 .157
FVAR HASSIM .80
FVAR C91 .054
FVAR C92 .68
FVAR ASSADJ .97 ( LOWER TO INCREASE )
FVAR C90 -.436


: STFIX STVASSIM F@ HUNGER F@ F* ONE  ( adjust assimilation when starving )
   FSWAP F- F* ;


: EXCRETE  WTEM F@ C40 F@ F^ I SIZE F@   ( excretion rate for group I )
  C90 F@  F^ F* C91 F@ F* ZCHECK
  ONE FSWAP F- ASSADJ F@ F* ( STARV?
  @ 1 = ) IF ( STFIX ) THEN I
  CONSUMP F@ F* ZCHECK I FECES F! ;



                      ( STATE EQUATION )
```

```
: EBALANCE                          ( integration for carp size in group I )
      I CONSUMP F@ I FECES   F@ F-
                I   RESPIRE F@ F-
                    STEP F*   CARPC F/
                 I  SIZE F@ F+ ZCHECK
                  I SIZE F!      ;


(--------------------------------------------------------------------------)
(--------------------------------------------------------------------------)
(                   MORTALITY SUBMODEL                                     )
                        - IHF3S.NHS                                        )
(--------------------------------------------------------------------------)
(--------------------------------------------------------------------------)


: ADJKILL I SIZE F@ FIXS 300 >             ( calc mortality coefficient )
        IF YEAR @ 6 >
        IF YEAR @ MORT.TAB F@ I FKILL F!
   ELSE WTEM F@ FIXS  8 >
            IF YEAR @ MORT.TAB F@
                I  FKILL F!
        ELSE WINTERKILL F@ I FKILL F!
            THEN
           THEN
        ELSE WTEM F@ FIXS  8 >
 IF I SIZE F@ LN MRTC1 F@ F* MRTC2
    F@ F+   I  FKILL F!
      ELSE WINTERKILL F@ I FKILL F!
      THEN
    THEN ;


: FDIE                                ( calc mortality rate   )
      ( HUNGER F@ STARVEKILL F@
        F*  )
        I  FKILL F@ F+
    I FNUM F@ F* ZCHECK I FMORT F!
;


FVAR FNUMR 0
FVAR C61 .5
FVAR FNUMR2 0
FVAR FNUMR3 0
```

```
: POPSIZE I FMORT F@ FCHS STEP F*      (  integrate for number left in group
  I FNUM F@ F+  ZCHECK FDUP I FNUM F!                  I    )
   C61 F@ F+ FIXS FLTS I FNUMR
                F! ;
```